



FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study program/ Specialization:

Offshore Risk Management

Spring semester, 2011

Open

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Title of thesis:

A further development of the Extended Risk Based Inspection methodology – guidelines and performance

Credits (ECTS): 30

Key words:

Risk Based Inspection, Risk Based Verification, Integrity Management, Maintenance, Uncertainty Analysis, Sensitivity Analysis

Pages: 71

Stavanger, 08.06.2011

ABSTRACT

Risk Based Inspection (RBI) is a much used method for planning inspection intervals in the oil and gas industry. The RBI method has over the recent years proved to show fruitful results with regards to proactive risk measures and continues to show results of increased safety, more reliable and predictable systems and a more economical routine for maintenance and inspection activities. However, some weaknesses in the method have been discovered; the method lacks a clear definition of risk and avoids assessing the uncertainties in calculations, data and judgements which potentially can lead to unwanted consequences. In order to assess this weakness, the ERBI method was developed by Selvik, Scarf et al. (2010). The basic idea behind the method is that uncertainties are communicated to the management through an extended uncertainty evaluation which integrates the results from the risk analysis and the uncertainty analysis. This thesis presents and discusses the ERBI methodology and provides an enhanced description of how to perform the ERBI method. The methodology is taken a step further; from a theoretical framework to a recommendation of practice. The recommended practice enhances some of the basic ideas of the ERBI methodology and maximises the benefits by using the method. The additional assessments of uncertainty and sensitivity in the ERBI methodology produce some increase in the time needed to perform the process, as well as resources required. The purpose of the thesis is to show that with an effective method of performing the ERBI, the increase of resources can be minimal – without compromising on the safety.

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ACKNOWLEDGEMENTS

I am very grateful for all feedback and support provided by my supervisor, Terje Aven, during the course of writing this thesis. Pointers given throughout the process have been helpful in improving the thesis as well as inspiring the writing.

I would also like to thank Ole Jørgen Melleby and the rest of the team at Bureau Veritas for wonderful support, a good working environment and valuable insight in the maintenance/oil & gas industry.

DEFINITIONS

Acceptance Criteria:

Specified indicators or measures providing an acceptable safety level and that are used in assessing the ability of a component, structure, or system, to perform its intended function (DNV 2009).

ALARP Process:

The risk should be reduced to a level that is As Low As Reasonably Practicable. This Principle means that the benefits of a measure should be assessed in relation to the disadvantages or costs of the measure. I.e. an identified measure should be implemented unless it cannot be documented that there is an unreasonable disparity ("gross disproportion") between costs/disadvantages and benefits (Aven 2008).

Consequence of Failure (CoF):

The outcome of a failure. This may be expressed, for example, in terms of safety to personnel, economic loss, damage to the environment (DNV 2009).

Degradation:

The reduction of a component's ability to carry out its function (DNV 2009).

Failure:

An event affecting a component or a system and causing one or both of the following effects:

- Loss of component or system function
- Deterioration of functional capacity to such an extent that the safety of the installation, personnel or environment is significantly reduced (DNV 2009).

Fatal Accident Rate:

The expected number of fatalities per 100 million hours of exposure (Aven 2008).

Downtime:

The time interval during which an item is in the down state which is characterised either by a fault, or by a possible inability to perform a required function, e.g. during preventive maintenance (NORSOK 1998).

E[NPV]:

Expected Net Present Value: $NPV = \sum_{t=0}^T \frac{C_t}{(1+r)^t}$, where C_t is the cash flow in year t , T the time period, r_t the discount rate.

Failure mode:

The effect by which a failure is observed on the failed item (NORSOK 1998).

Failure rate:

Number of failures relative to the corresponding operational time (NORSOK 1998).

Potential Loss of Life:

The expected number of fatalities over a year (Aven 2008).

Precautionary Principle:

In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation (1992 Rio Declaration).

Preventive maintenance:

Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item (NORSOK 1998).

Probability:

We can differentiate between two main interpretations of probability (Aven 2008):

- Relative frequency-interpreted probabilities (P_f) interpret probability in the classical statistical sense as the relative fraction of times the event occur if the situation analysed were hypothetically repeated an infinite number of times.
- Subjective knowledge based (Bayesian) probability (P) is a measure of uncertainty about events and outcomes (consequences), seen through the eyes of the assessor and based on some background information and knowledge.

Reliability:

The ability of an item to perform a required function under given conditions for a given time interval (NORSOK 1998).

Risk:

The adopted risk perspective used in this thesis has the general definition given in (Aven 2008), where risk is defined as the two-dimensional combination of; events A and the consequences of these events C , and the associated uncertainties U (about what will be the outcome). This can be written as (A, C, U) or simply (C, U) .

Risk Management:

Risk management is defined as all measurements and activities carried out to manage risk. This involves all types of risk and all activities, conditions, events, etc. performed in order to secure an organisation or a projects ability to reach its goals and vision (Aven 2008).

Uncertainty:

We can distinguish between two main classifications of uncertainty; parameter uncertainty and model uncertainty, where parameter uncertainty refers to various kinds of measurement error, sampling errors, misclassifications etc. and model uncertainty derives from oversimplification, and relationship errors in models, among other things (Levin 2005).

We also distinguish between epistemic and aleatory uncertainty. Epistemic and aleatory uncertainty has been defined in the following ways:

- Epistemic uncertainty: a result of lack of knowledge (Apeland, Aven et al. 2002)
- Aleatory uncertainty: a fundamental or inherent randomness in the natural phenomena of the world (Nilsen and Aven 2003)

Verification:

An examination to confirm that an activity, a product or a service is in accordance with specified requirements (DNV 2000).

ABBREVIATIONS

ALARP – As Low As Reasonably Practicable
API – American Petroleum Institute
CoF – Consequence of Failure
CRA – Corrosion Resistant Alloys
DNV – Det Norske Veritas
ERBI – Extended Risk Based Inspection
FEED – Front-End Engineering and Design
FMEA – Failure Mode and Effects Analysis
FMECA – Failure Mode, Effects and Criticality Analysis
FORM – First Order Reliability Method
HAZID – Hazard Identification study
HAZOP – Hazard and Operability study
HE – Hydrogen Embrittlement
HES - Health, Environment and Safety
HIC – Hydrogen Induced Cracking
HISC – Hydrogen Induced Stress Cracking
HSE – Health and Safety Executive (UK)
IM – Integrity Management
IMS – Integrity Management System
LCC – Life Cycle Cost
MSI - Maintenance Significant Items
NPV – Net Present Value
PLL – Potential Loss of Lives
PM – Preventative Maintenance
PoF – Probability of Failure
QRA – Quantitative Risk Assessment
RAC – Risk Acceptance Criterion
RBI – Risk Based Inspections
RBV – Risk Based Verification
RCM – Reliability Centred Maintenance
RoF – Risk of Failure
ROV – Remotely Operated underwater Vehicle
RTS – Remote Tie-in System
SCE – Safety Critical Elements
SPS – Subsea Production System

1. INTRODUCTION

1.1 BACKGROUND

Maintenance is a fairly new phenomenon, and has not always been as integrated in the system life cycle as today. By maintaining a system in its functional state, value is created through the avoidance of downtime. The value created is often seen as very indirect, as the functioning state is deemed the normal state to be in; the anomaly is rather when the system is not functioning, and value is lost due reduced and/or delayed production. The costs of maintenance and inspection may therefore often seem very large and with few visible results. If the maintenance procedure works in an efficient manner, then the production will continue as planned, without interruption – hence presumed as “normal production” and the economical values from the maintenance work are not given its deserved credits for the result. Through three generations of maintenance management the connections between maintenance and product quality and to what extent equipment failure effects safety, environment and costs has experienced an increasing awareness in different parts of the industry. Maintenance routines and other methods to ensure a reliable system, are today integrated parts of a project. As seen in the figure below, the increasing interest in maintenance can be traced back to the 1930's. By the third generation, Risk Centred Maintenance (RCM) and Risk Based Inspection (RBI) have demanded a central position amongst the different maintenance techniques. The popularity of these methodologies is mainly caused by the many challenges faced when trying to ensure a reliable system at the lowest cost possible. Efficient and appropriate techniques must be selected, different types of failure processes must be assessed and so on. Also the continually increasing standards and regulations regarding safety to personnel and environmental preservations has lead to increased awareness of risk management. Both industry and society have growing expectations to the reliability and safety of systems – perhaps especially in the offshore industry. This has lead to a series of methods and theories of how to keep risk at the acceptable level (Moubay 1997).

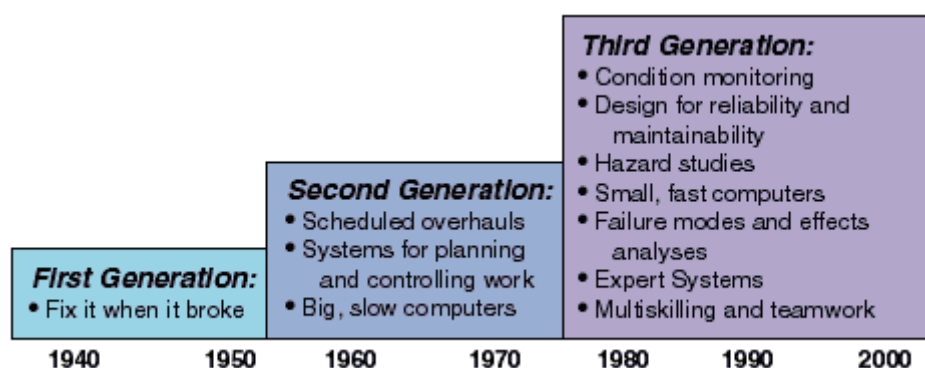


FIGURE 1 CHANGING MAINENANCE TECHNIQUES (MOUBRAY, 1997)

A progressive pattern of deterioration and functional degradation is one of the most important characteristics of deterioration and failures. This has been illustrated in the figure below. The pattern of degradation is illustrated by the parameters

- Normal state, τ_N
- Symptomatic state, τ_D

The progressive pattern of degradation of a system can tell us about how often maintenance is needed as well as the criticality of monitoring and inspection routines. If, for example, τ_N is unpredictable time-based maintenance cannot be applied. If τ_D is very short, on the other hand, condition-based maintenance cannot be adopted. Failure may strike sudden, or at least be recognized as sudden, but the deterioration process that induces the failure may have been gradually increasing and will therefore also be detectable with the correct measures (Takata, Kirnura et al. 2004).

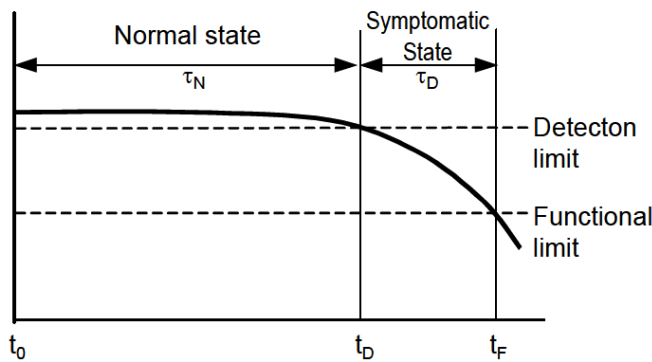


FIGURE 2 PROGRESSIVE PATTERN OF DETERIORATION OR FUNCTIONAL DEGRADATION. (TAKATA ET AL., 2004)

Integrity Management (IM) processes are today widely used in industries across the world and have the objective of avoiding major accidents, as well as ensuring that all activities and structures comply with authority requirements, rules and regulations, codes and standards and keeping the maintenance costs down. IM is particularly an important part of all offshore activities to ensure both public and environmental safety and maximising the operating up-time, and hence also production and life cycle value.

Risk Based Inspection (RBI) is a method which can be categorised as integrity management. The objective of the RBI methodology is to create an inspection plan which shows the most preferable inspection intervals, i.e. in advance of a failure but yet as seldom as possible. Inspections are in most cases very expensive and are therefore deemed somewhat unpopular however necessary they may be.

Verification of offshore installations is another method of integrity management. Verification constitutes a systematic and independent examination of the various phases in the life of a system to determine whether it has (or continues to have) sufficient integrity for its purpose. The activities performed are meant to identify errors and failures. The verification plan focuses on integrity, safety and business risk. It is a sampling process and includes document review, checks using calculations, physical examination, testing or witnessing of tests, audit and confirmation of records during the installation's lifetime. Risk Based Verification (RBV) is a methodology which includes a risk perspective and risk analysis in order to produce a verification scheme. Some of the advantages of having a risk based perspective when assessing such a scheme is improved verification due to better knowledge of the system, its risk drivers and deficiencies.

Both the RBV and RBI methodologies use, amongst other things, equipment history and likely consequences of failure to determine inspection regimes focused on actual risks to prevent accidents from occurring. Different systems and software packages as well as variations in

methods for finding the deterioration information have led seemingly similar RBI assessments to produce very different results depending on the methods and systems used. An example of this is a study which was undertaken by the British Health and Safety Laboratory using several example cases to extract the differences in these systems. A few of the main findings were:

1. Considerable variation in the selection of damage mechanisms for assessment was apparent.
2. Significant variability was found in the assignment of the importance of damage mechanisms; different conclusions, regarding the activity of a damage mechanism, were drawn from identical data.
3. Where software systems were used and calculations of the consequences were made, it was not transparent what assumptions had been made; details were frequently hidden in the "black box".

The findings show a clear lack of consistency in the use of data bases amongst the different companies. Generic data allow room for personal interpretation and simplifications which seem to produce different conclusions in practically identical cases. This is only one example of how sensitive data can be and how important it is to include uncertainty and sensitivity in a risk picture. For further information about these results, the reader is referred to (Geary 2002).

The deterioration processes of equipment and structures are often of a highly uncertain nature, and so generic data and assumptions are commonly used. In practice, systems cannot be characterized exactly – the knowledge of the underlying processes is incomplete. Deterioration processes will follow different patterns both time wise and in terms of location in the facility depending on production characteristics, exposure to aggressive environments, etc. It can also occur due to errors or flaws during manufacturing and executions. The generic values included in the planning of RBI are used as truths and the calculations and estimations of assumptions and believed values are relied upon without knowledge of where the numbers have their origin. This creates a major gap from the reality of the world and the basis of which we make decisions about inspection intervals and general system safety. One needs to come to term with the fact that objective numbers cannot provide a full risk description, and rather embrace the uncertainties that exist and use them for what they are worth in order to gain understanding and knowledge. Before one realizes the value in these uncertainties, when assessed correctly, a full risk picture will not be provided – the results are simply beliefs with a larger or smaller degree of uncertainty and assumptions, unreliable for decision making and unreliable for securing the safety of a system, the environment and the personnel working there.

The RBI method as performed today does not include the assessment of uncertainty – it assesses risk only as a combination of probabilities and failure events and consequences. A broader risk perspective is needed in order to take uncertainty into account and hence also expand the RBI methodology.

The necessity of an improved methodology has led to the development of a new and improved RBI, namely the Extended RBI (ERBI), developed by (Selvik, Scarf et al. 2010). The ERBI has the purpose of increasing focus on the uncertainties and additional impact the results may provide in the phase of decision making. The new methodology has the purpose of performing as a solid basis for decision making which will further lead to improved system safety, cost efficient performance as well as ensuring that all rules and regulations are met.

However, the extension of the RBI will entail an increase in both time and resources spent on the inspection plan. To much focus on uncertainty factors in a risk assessment may very well contribute confusingly if not handled and presented correctly. Hence the embracement of such a methodology cannot be expected without a presentation of performance and a set of guidelines to ensure the correct approach, as well as the persuasion that the methodology will pay off in the long run with regards to resources spent.

1.2 PURPOSE OF THESIS

The purpose of the thesis is to provide a recommended practice of the ERBI methodology which includes measures which will make the extended RBI more attractive both with regards to simplicity as well as concerns about the necessary resources needed.

It is not to be set aside the scepticism of spending extra resources on an extended RBI, when the normal RBI is so commonly embraced. With a few simple measures it is believed that the ERBI method does not necessarily need to implicate spending extra time and costs on the inspection planning. Confusion concerning the meaning and proper assessment of the uncertainty factors can at the same time be eliminated with a set of guidelines in how this process is performed and maybe most important; how the results are presented.

As of today the ERBI methodology only exists as a short elucidation of the basic framework and idea behind the methodology. This thesis wishes to provide a fuller and more thorough description of the ERBI methodology which further explains the how's and the why's of the methodology, as well as a recommended practice of performance.

One of the advantages with the ERBI methodology is that it is also believed that a bridge between the RBI and other risk assessments, in particular RBV, can be made in order to enhance effectiveness and reduce overall related costs. The thesis has as purpose to show this connection and provide a method for how this bridge can be built in practice.

1.3 CONTENT

An introduction of existing methodologies is initially given in order to provide the reader with information about which methods are used in today's industry, their objectives and some background information. Most focus will be given on the RBI, as this will be further developed in the continuing parts of the thesis.

Chapter 2 introduces the reader to the terms of RCM, RBI, Verification, Sensitivity Analyses and Uncertainty Analyses. The chapter contains simple descriptions of the methods of how they are used and what purpose they contain.

The following sections of the thesis introduce the reader to the Extended Risk Based Inspection.

In Chapter 3 a description of a the new and improved method of RBI developed by Selvik, Scarf et al. (2010), the Extended Risk Based Inspection methodology, is explained. The framework for the methodology is also provided.

In relation to the ERBI, the author proposes a recommended practice for the methodology. This is given in Chapter 4. Here, all phases of the ERBI process are assessed and further developed with the intention of providing examples and recommendations of how to perform the ERBI.

The recommended practice also includes a method for including risk based verification (RBV) for higher efficiency and quality – this is provided in [Chapter 5](#). The necessary regulations in which the RBV must work in compliance with are introduced, as well as further information about the RBV and differences from the proposed extended version. Discussion of potential benefits, practice and motivation will also be included in relation to the extended risk based verification framework.

The report is divided into two major parts where Part I comprises the theory – i.e. all of the above.

Part II consists of an example case in order to demonstrate the extended RBI and RBV including the author's recommendation for practice. The first section of part II gives a short introduction of the Trym installation ([Chapter 6](#)) and continues with a descriptive execution of the ERBI planning and verification ([Chapter 7](#)). The results of the ERBI are discussed in [Chapter 8](#).

Concluding remarks are given in [Chapter 9](#).

PART I:

INTRODUCTION TO A FEW COMMON METHODS FOR PREVENTIVE MAINTENANCE AND THE ERBI METHODOLOGY

2. BASIC CONCEPTS AND METHODOLOGIES

This chapter describes existing methods for preventive maintenance which are commonly used in the industry today. The chapter gives a brief introduction which explains and provides the reader with relevant background information about RCM, RBI and Verification. This information gives the reader an idea of how preventive maintenance can be, and often is, performed in today's industry. Two methods of analysis are also explained in this chapter – sensitivity analysis and uncertainty analysis.

The RBI method has been given extra attention as this is relevant for the following introduction to the Extended RBI in chapter 3. Chapter 2.2 describes the RBI framework and takes a closer look at how the RBI is performed based on existing recommendations.

2.1 RELIABILITY CENTRED MAINTENANCE

Reliability Centred Maintenance is a methodology which over the last decades has become very popular in the industry. RCM is a widely accepted methodology, and has proved to offer an efficient strategy for preventive maintenance optimisation. With its objectives to reduce maintenance costs and at the same time increase reliability and safety, it provides a framework which responds to the challenges of cost efficiency, safety and detection of failure modes (Selvik and Aven 2010).

The RCM methodology describes a procedure which includes defining the following:

- functional states
- failure modes
- what causes the system to fail
- what can be done to predict or prevent each failure
- what should be done if a proactive task cannot be found

In assessing the listed problems above, a Failure Mode, Effects and Criticality Analysis (FMECA) can be used.

When applying the RCM methodology, the first task to assess is the decision of what equipment is to be analysed. Clearly defined asset reliability criteria are recommended, which involves identifying all the unwanted consequences of failures which can occur. When defining these concerns one needs to take into account both safety concerns, operability concerns and economical concerns. Further concerns can be added as seen fit to the project. The results from this screening phase is later fed into a RCM logic for specification on preventive maintenance (PM) tasks. The RCM logic tree is a set of questions designed to determine the ultimate consequence of failure. The figure below is called the RCM-filter. This is a simplified method of looking at the RCM logic, the filtering of potentially critical components and economical components and how to reach the final preventive maintenance program (Bloom 2006).

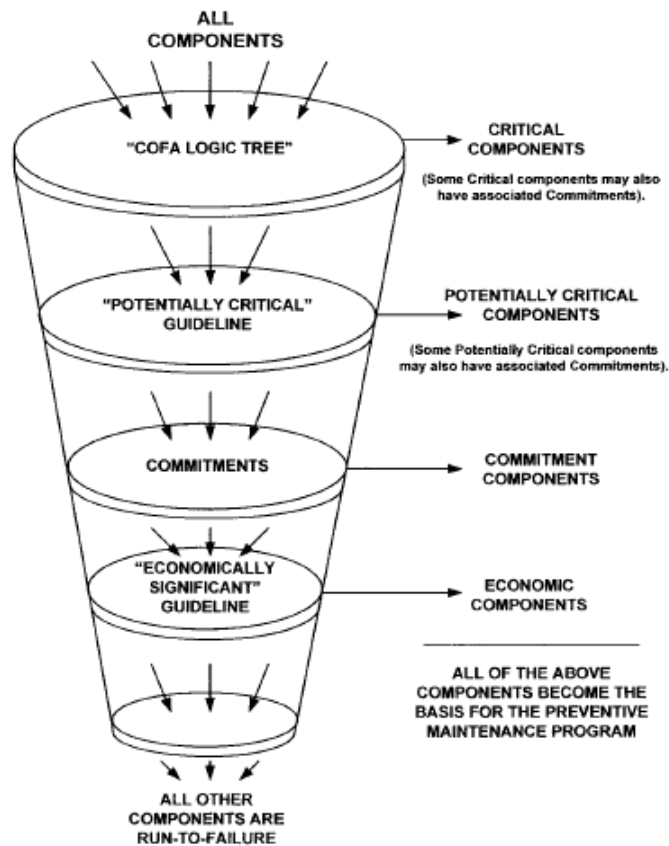


FIGURE 3 RCM-FILTER (BLOOM, 2006)

Continuous monitoring for changes is necessary to keep the maintenance program effective and relevant as equipment is replaced and work routines change.

2.2 RISK BASED INSPECTION

Risk based inspection (RBI) is a decision-making technique for inspection planning based on risk. The consequences of system failure, either economical or with regards to HES, has been the main motivation for focusing on integrity management, maintenance and inspections.

The RBI methodology ensures a systematic and documented breakdown of the installation's risks, highlighting high-risk equipment and risk drivers by identifying the optimal inspection/monitoring methods according to the degradation mechanisms and the agreed inspection strategies. The documentation of these high-risk assets ensures an effective inspection, where efforts are focused on these items and reduced on the low-risk items. By setting risk acceptance criteria, the RBI contributes in a pro-active manner to secure that the system does not exceed this limit.

RBI is commonly used in the planning of inspections in systems such as offshore structures and pipelines. The approach takes basis in a quantification of risk, not only for components separately, but also for the system or installation as a whole. In compliance with given requirements and acceptance criteria, RBI is applied in order to secure an economical and safe operation throughout the anticipated service life. Degradation of the assets, e.g. corrosion or fatigue crack growth etc., is a common process and will often become present in a more or less serious degree. The acceptance criteria, usually set during the design phase, determine whether the degradation of the system is acceptable or not. To ensure that the damage is within the

acceptable limits it is necessary to control the development of deterioration. In the controlling of this it may prove practical to perform routine inspections of the system. RBI assesses risk to support the inspection planning. If found required, corrective maintenance procedures should be executed.

2.2.1 INSPECTION AND INSPECTION-PLANNING

Inspections have the objective of minimising risks due to degradation of systems and equipment. Inspections are usually performed periodically in order to view progression and detect damage to equipment. This can either be done by performing a physical inspection, in the means of a visual examination, technical instruments or by inspection of design plans and calculations. This is performed in order to ensure that integrity of the system is maintained according to the design. The inspection activities provide specific, relevant, accurate and timely information to the management on the condition of assets.

An inspection plan is designed to define the inspection criteria, i.e. to determine what should be inspected, how the inspection takes place, characteristics to be inspected, required test equipment, work centre, inspection specifications and with due regard for the policy and the risks to its achievement. In the planning of inspections, it is preferred to know - to some degree - what to expect and what to be particularly aware of. This will make the inspections considerably more effective and at the same time more thorough. When deciding what should be inspected, a risk assessment is common practice. The risk assessment should reveal information about the risk related to a project. Equipment that are characterised as high-risk should be under closer surveillance and need a high-frequency and thorough inspection plan. The inspection plan should in other words reflect on the criticality of the equipment (DNV 2009).

The inspections imply direct cost and also risks for maintenance introduced failures. The benefits of the inspection may therefore be obscured by the economical consequences, especially in situations where the inspection has an impact on the operation of the system. The balance between inspections and economical consequences must therefore be evaluated such that the benefits of the inspection override the economical consequences implied by the inspection itself. Maintenance planning is about balancing these concerns (Selvik, Scarf et al. 2010).

The results of the inspection plan provides a method for indentifying threats to a system sufficiently early so that they can be corrected cost effectively with no considerable impact on asset integrity or safety. For the inspection plan to be continuously relevant over time, a register over equipment should be in place and maintained current with the condition of assets and their inspection history.

Inspection planning based on the RBI approach is a rational and cost efficient decision framework for determining

- where to inspect
- what to inspect
- how to inspect
- when to inspect

and at the same time ensuring and documenting that requirements to the safety of personnel and environment are fulfilled (Faber 2002).

Inspection Planning is a process comprising three parts (DNV 2009):

1. Risk Based Inspection Analysis

The RBI Analysis defines the different parts of the system or structure that are to be inspected. A more thorough assessment is performed to find which degradation mechanisms should be considered and the date of the first inspection.

2. Development of an Inspection Frame Program

An Inspection Frame Program includes a long-term view of the expected inspections as well as experience and judgment related to the degradation which is not included in the RBI.

3. Detailed Inspection Plan

The final Detailed Inspection Plan is a result of interpreting the findings in the RBI analyses and other relevant experiences. The plan should cover type and technique of inspection, required preparation, the necessary inspection coverage and level of quality of inspection.

2.2.2 METHODOLOGY

The RBI approach comprises the consequences of failure (CoF) and the probability of failure (PoF). These are calculated separately, and when added together they result in risk of failure (RoF). By using probabilistic methods one can calculate the extent of degradation and hence allow variation and uncertainties in process parameters. By doing this, degradation rates and damage extent are being accounted for. By calculating the CoF, attention is focused on the areas where it will have the most effect. If there are significant uncertainties in the outcomes, these can be modelled by investigating the probabilities of the various outcomes using an event tree approach.

The calculated PoF, CoF and RoF are usually parts of a QRA, and include modelling of the degradation process. These are further used in a qualitative or semi-quantitative risk matrix to express the risk level and relationship between the PoF and CoF. The common methodology is usually based on both qualitative and quantitative, although it is possible to choose either one separately and get a strictly expert judgment based approach or model-based approach.

The RBI assesses risk as a combination of probabilities and failure events and consequences in the much used risk perspective: Risk = Probability x Consequence. In the API RBI methodology, the probability of failure, $P(t)$, is a function of time due to the belief that the damage accumulates with time. The consequence of failure is assumed to be invariant with time. Hence, the equation becomes

$$R(t) = P(t) \cdot CA \quad (1)$$

Where CA indicates the consequence impact area, i.e. area based risk. This can be calculated similarly for economical risk. Note that the risk will by this methodology vary with time since the probability of failure is a function of time (Henry and Osage 2008).

Variations in the methodology exist, but they are all based on the fundamental pillars defined by technical standards such as (API 2008) and (DNV 2009). The figure below shows API's recommended practice for the RBI work process:

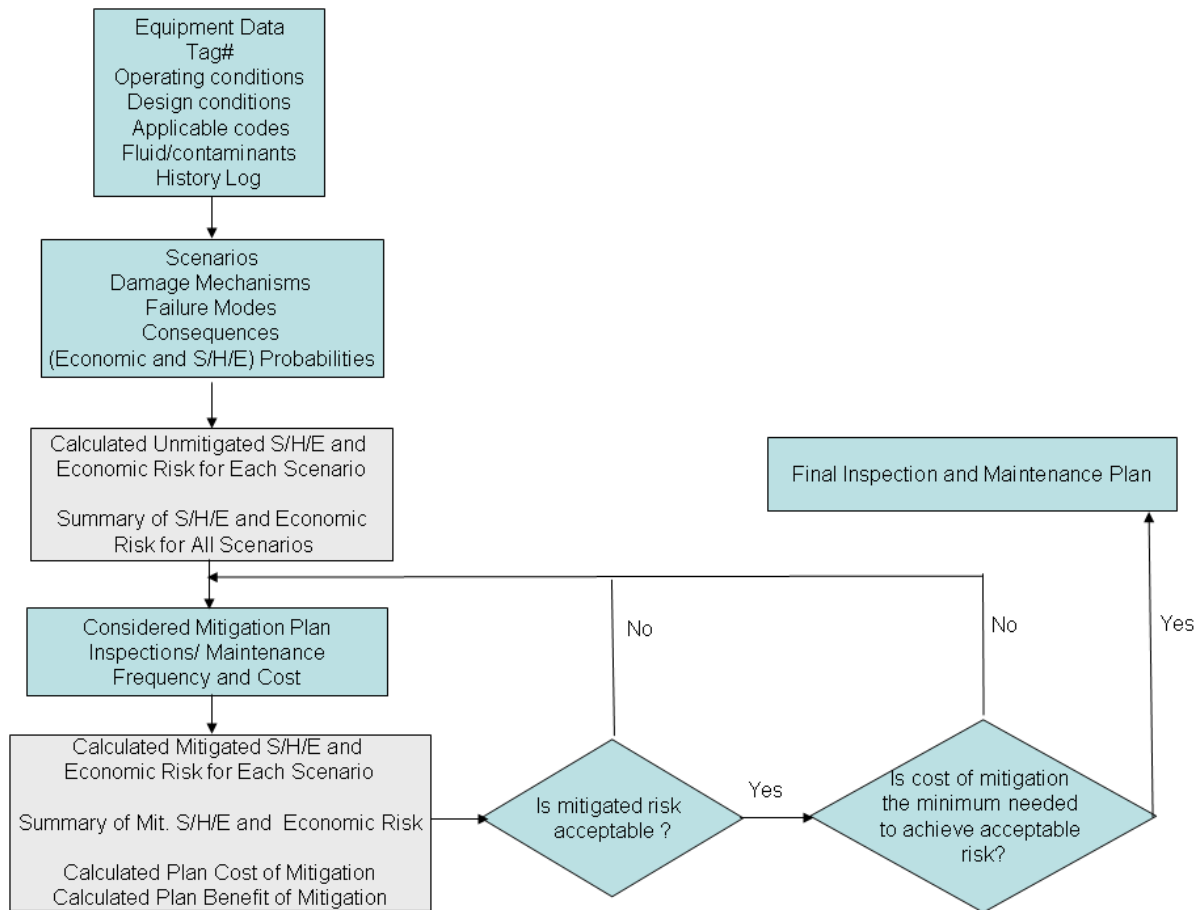


FIGURE 4 RBI WORK PROCESS (API, 2008)

The figure shows a general recommended working process which should be applied at different levels of the assessment. The process can be divided into five stages (similar to the DNV recommendation):

1. Information gathering
2. Screening assessment
3. Detailed assessment
4. Planning / Inspection interval assessment
5. Execution and evaluation

Information gathering is typically input from sources like equipment list, data sheets, drawings and diagrams from the design phase etc. In the absence of such information, assumptions based on judgment and experience is recommended.

In the screening assessment higher level elements that are judged to make a significant contribution to the risk level are identified by the use of for example FMEA or risk matrices. Different scenarios are assessed in order to find the different failure modes of the system. The high-level screening excludes low risk components from being included further in the process, thus making it more effective as low risk items will require minimal inspection supported by maintenance. DNV recommends the use of five levels, as shown in the figure below.

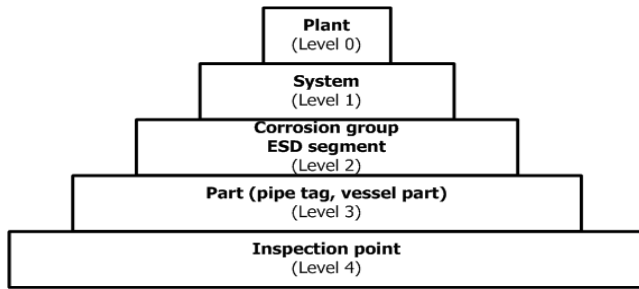


FIGURE 5 EQUIPMENT LEVEL HIERARCHY, (DNV 2009)

The detailed assessment involves the elements from the screening judged to have medium or high risk. These items need to be broken down to lower levels to be evaluated in more detail. Calculations of PoF and CoF are used to rank the items which further should be separated into economic, environmental and safety risks.

Probability of failure is defined as the probability of an event occurring per unit time (DNV 2009). In order to be able to say something about this, relevant data of degradation is needed. A good understanding of the degradation process is critical in the finding of a model that describes the expected failure rates. The degradation process of different materials can be estimated by the use of historical databases of similar equipment in similar environmental conditions.

The consequence of failure can be calculated in terms of Potential Loss of Lives (PLL), Expected NPV ($E[NPV]$) and volume of pollutants spilled; for safety, economy and environmental consequences respectively. A separate evaluation of these three consequence types, described either in the shape of a qualitative ranking scale or a risk matrix, is recommended. The ranking scale is based on ranking the consequences on a scale from A to E, where A equals insignificant consequences and E equals either multiple fatalities, massive environmental effects or extensive economic damage.

Based on the assessments of PoF and CoF a risk matrix is recommended. A 5x5 risk matrix is recommended:

TABLE 1 EXAMPLE OF RISK MATRIX (DNV 2009)

| PoF Ranking | PoF Description | A | B | C | D | E |
|--------------------|--|-----------------------------|--|--|---|---|
| 5 | (1) In a small population, one or more failures can be expected annually. (2) Failure has occurred several times a year in the location. | YELLOW | RED | RED | RED | RED |
| 4 | (1) In a large population, one or more failures can be expected annually. (2) Failure has occurred several times a year in operating company. | YELLOW | YELLOW | RED | RED | RED |
| 3 | (1) Several failures may occur during the life of the installation for a system comprising a small number of components. (2) Failure has occurred in the operating company. | GREEN | YELLOW | YELLOW | RED | RED |
| 2 | (1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry. | GREEN | GREEN | YELLOW | YELLOW | RED |
| 1 | (1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry. | GREEN | GREEN | GREEN | YELLOW | YELLOW |
| CoF Types | Safety | No Injury | Minor Injury Absence < 2 days | Major Injury Absence > 2 days | Single Fatality | Multiple Fatalities |
| | Environment | No pollution | Minor local effect. Can be cleaned up easily. | Significant local effect. Will take more than 1 man week to remove. | Pollution has significant effect upon the surrounding ecosystem (e.g. population of birds or fish). | Pollution that can cause massive and irreparable damage to ecosystem. |
| | Business | No downtime or asset damage | < € 10.000 damage or downtime < one shift | < € 100.000 damage or downtime < 4 shifts | < € 1.000.000 damage or downtime < one month | < € 10.000.000 damage or downtime one year |
| CoF Ranking | | A | B | C | D | E |

The results from the PoF, CoF and risk matrix should be updated when needed and the validity of assumptions and correctness of data should be checked.

Planning / Inspection interval assessment is the assessment of a preliminary inspection plan. Here all data up to this point is being evaluated along with other factors like logistics in order to produce a final executable inspection plan. Risk acceptance criteria or the ALARP (As Low As Reasonably Practicable) principle should be taken into consideration during this phase.

Execution and evaluation considers all the recommendations and guidelines presented in the above sections. Additional considerations to data quality, working process, updating, data storage and infrastructure capacity are also taken into account at this stage.

Inspection activity is subject to appropriate verification of its performance (DNV 2009).

2.3 VERIFICATION

The verification of a system or an item is performed in order to confirm that the asset under inspection is in a condition that complies with the technical requirements. The verification process consists of a systematic and independent examination of the various phases in a system's life to ensure sufficient integrity for its purpose. Verification is performed complimentary to the design, construction and operations activities, and hence it is inevitable that some work is duplicated. However, the desired verification scheme has the goal of minimising additional work and cost and at the same time maximising its effectiveness (DNV 2000).

The Petroleum Safety Authority Norway state that a verification basis shall be established for the overall activities after assessing the scope, method and degree of independence of the verification. For instance there will normally be a need to verify compliance with the HES requirements. In the establishment of the degree of independence it is entailed that the verifications shall be carried out by a party other than the one that has carried out the work to be verified or the party that has prepared the verification basis. An overall assessment of the results of the verifications shall also be carried out with recommended organisational independence for the reporting (The Petroleum Safety Authority Norway 2010).

Before verification activities commence, a verification scheme is written in order to ensure that the safety critical elements and specified system or equipment are or (in the case of failure and extensive degradation, etc.) will be, in good condition. Verification activities based on the verification scheme are expected to identify errors or failures in the work associated, i.e. secure that they will perform, and remain able to perform, in accordance with the performance standards set for them. The main objective of these activities is to minimise the risk associated with errors and degradation of the system, threatening the safety of personnel and the environment, as well as the economical aspects in case of failure.

2.4 SENSITIVITY ANALYSIS

Sensitivity analyses are not to be mistaken for uncertainty analyses, although they have some of the same functions and intentions. Sensitivity studies are performed in order to rule out the possibility that minor changes to assumptions and/or data will alter the conclusions of the risk analysis. Results from the sensitivity study show how the results depend on various conditions and assumptions. The sensitivity analysis highlights the importance of key quantities and can provide a basis for assessing uncertainty (Aven 2008).

In QRA's sensitivity studies are required according to HES management regulations in order to illustrate the robustness of the risk model, and are as such an illustration of the uncertainties (Vinnem 2007). The sensitivity of the results in a risk analysis or QRA can be shown by using radar charts, see figure 6, or tornado charts, see figure 7.

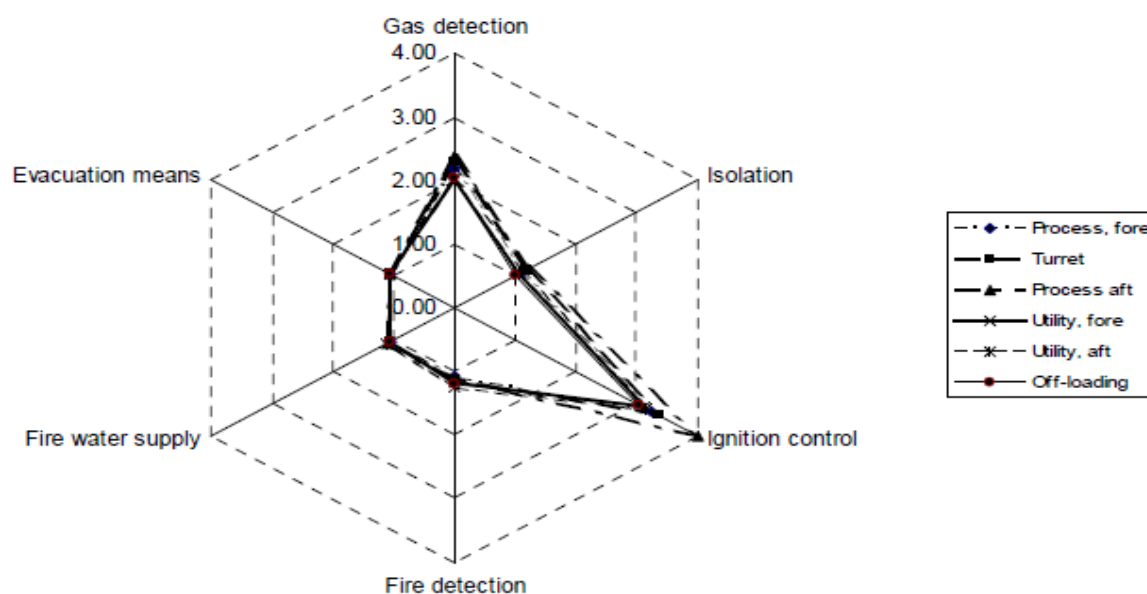


FIGURE 6 RADAR CHART (VINNEM)

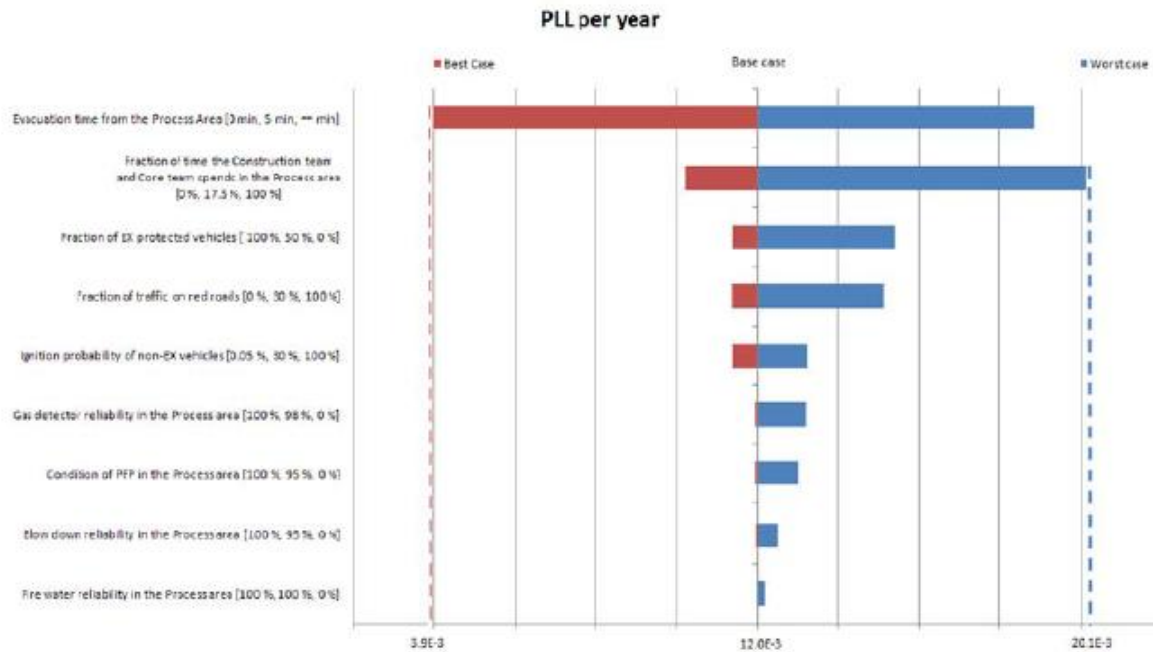


FIGURE 7 TORNADO CHART (VINNEM)

2.5 UNCERTAINTY ANALYSIS

To assess uncertainties in risk analyses, an uncertainty analysis is much used and recommended. There is however a lack of agreement within the field of risk management on how to perform an uncertainty analysis. Many find a quantitative method easy to relate to, whilst others see the advantages of a qualitative or semi-quantitative approach. Rocquigny, Devictor et al. (2008) has written a guide to quantitative uncertainty analysis and management in industry which describes a framework for uncertainty modelling and characterisations. The book uses largely probabilities and probability distributions in the assessments of uncertainty, which requires a high knowledge within these fields and can as well seem to be a tedious process to complete.

The semi-quantitative approach to uncertainty analysis is often deemed as a simplified method compared to the quantitative approach. The reason for this is believed to lie in the representation of risk being understandable for someone without advanced knowledge about probability and the different probability distributions. The results are expressed qualitatively and therefore provide a more thorough explanation of what the uncertainty means in relation to the safety and other relevant aspects of the risk analysis. For example, if the uncertainty is considered to be low, this may constitute that the background knowledge is considered to be of a very precise and relevant character. A number of other characteristics may need to be fulfilled in order to determine the level of uncertainty. The qualitative approach on the other hand, often reveals a certain probability distribution as a description of the uncertainty. When using, say, a Weibull distribution, we compute $P(Z \leq z)$ and accept the use of a specific model as a part of the background knowledge in which the assessment is based upon. This does not only add confusion as to what $P(Z \leq z)$ really represents, but it also adds additional model uncertainties relating to the use of the distribution and calculation procedures.

The added information from the uncertainty analysis helps create a descriptive picture of the risks involved which includes knowledge of both more and less certain information. Being aware of the level of uncertainty entails the information that lie in the awareness and knowing the

weaknesses and facts one does not have the basis of finding. If this is accepted and acknowledged, specific boundaries of future events are not set, i.e. one does not exclude uncommon or unique events. This further involves being better equipped to handle prospective surprises as well as basing all decisions on a more realistic basis.

3. EXTENDED RISK BASED INSPECTION

The Extended Risk Based Inspection (ERBI) methodology was first introduced by (Selvik, Scarf et al. 2010). It is an extension of the RBI methodology, which includes the reflection of risk and uncertainties beyond expected values. This chapter explains the basic ERBI methodology – with similarities and differences from the RBI - and the complete ERBI framework.

3.1 THE ERBI METHODOLOGY

The probabilities (PoF) are calculations based on background knowledge like historical data (e.g. industry failure data), experiments and trials, expert judgements, etc. These sources will in many cases provide good expected values when used correctly, but they do not cover the entire risk picture. This is mainly because the values from these databases are retrieved from other sources which may or may not be similar to the system in focus. Inaccuracies can be caused by two main factors:

1. Limitations in the analyst's phenomenon knowledge
2. Deliberate simplifications introduced by the analyst

Where the first factor typically has relation to

- Highly complex systems and phenomena
- Interaction between human beings and technical equipment
- New systems and phenomena for which few or no models exist
- The quantities considered are associated with the uncertain conditions governing an unwanted scenario in the future

And the second factor typically has relation to

- Trade-offs forced between economy and the level of detail
- It is believed to serve its purpose sufficiently in spite of inaccuracies
- Convenient reductions of the analysis efforts.

(Nilsen and Aven 2003)

The risk assessments in the RBI methodology are based on background knowledge, expert judgments and insufficient databases which may all include assumptions that could conceal uncertainties that have not been addressed by the probabilistic assessments of the traditional RBI. The ERBI methodology acknowledges these uncertainties through the adoption of a broader risk perspective:

Risk is in the ERBI methodology defined as the two-dimensional combination of; events A and the consequences of these events C, and the associated uncertainty factor U_F (about what will be the outcome). This can be written as (A, C, U_F) or simply (C, U_F).

By this definition it is meant that risk is equal to the uncertainty about the consequences of an activity seen in relation to the severity of the consequences. By applying this definition of risk in the RBI methodology, the uncertainties are no longer hidden behind expected values and probabilities, but assessed as relevant information in order to accomplish a more complete picture of all aspects of risks. The probabilities and expected values are simply tools used to express the uncertainty related to future values of observable quantities.

Risk is described by (C, C^*, P, U_F, K) where C equals the consequences of the activity (including the initial events A), C^* is a prediction of C , U_F is the uncertainty factor about what value C will take, and P is the probability of specific events and consequences, given the background information K .

In the ERBI, where this description has been adopted, it means in practice that our predictions of the consequences of an event (degradation, failure, etc.) are described in connection to the uncertainties related to the predictions. The uncertainties in the background information given in order to produce predictions are assessed as vital information in the task of fully describing the associated risks.

The representation of the uncertainties depends on the probabilistic basis applied. In the subjective, Bayesian, approach focus is on observable quantities and how probabilities and probability distributions are used to describe uncertainty. The Bayesian approach considers probability as a measure of uncertainty about events and outcomes (consequences), seen through the eyes of the assessor and based on some background information and knowledge (Aven 2008).

All probabilities in ERBI are knowledge based (subjective) and used as a measure of uncertainty. The knowledge based interpretation of a probability, P , is necessary in order to simplify the analysis and calculations of PoF, as well as directly assessing the uncertainties. If we use a relative frequency-interpreted probability, P_f , in ERBI for the probability that a component fails during a certain time period, then P_f describes an unknown population fraction. This is because the probability is understood as the fraction of components that fail in this period when considering an infinite large population of similar components in similar conditions - which is unknown. This results in P_f to be replaced by estimates, but these estimates would be subject to uncertainties, and hence the methodology brakes down (Aven 2010).

RBI also depends largely on the acceptance criteria and uses this as a measure in order to provide acceptable safety levels and as relevant decision criteria. ERBI sees the need for a broader process in the decision-making context, where a decision cannot be justified by a simple comparison of probabilities. A simple requirement related to uncertainty about the performance should be avoided. The limitations in risk based inspection and inspection planning need to be taken into account as well as the difficulty in obtaining and specifying probabilities for certain quantities. This is referred to as Managerial Review and Judgement. It is a process that extends beyond the domain of the uncertainty analysis which concludes on the implications of the analysis and balance different concerns. The result is, for example, an acceptance of the uncertainties related to an activity, the need for design changes, the choice of an alternative, etc. (Aven 2003; Aven 2010).

The ERBI framework provides a basis for discussion and encourages the consultation and involvement of a wider range as more information is gathered through different phases and at different levels. The framework is intended to assist in setting the decision context; it does not make the decision for you.

Recall the five stages of the RBI process (DNV 2009):

1. Information gathering
2. Screening assessment

3. Detailed assessment
4. Planning / Inspection interval assessment
5. Execution and evaluation

In order to avoid the shortcomings of the RBI methodology, we include the assessment of uncertainty in the risk description and an extended process is introduced in ERBI (Selvik, Scarf et al. 2010):

1. Information gathering
2. Screening assessment
3. Detailed assessment
4. Inspection interval assessment
5. Uncertainty analysis
6. Uncertainty evaluation & representation
7. Managerial review and judgement
8. Decisions and implementation

All stages will be thoroughly described in the following sections of the report.

3.2 MOTIVATION

Predictions related to future degradation of equipment and systems are subject to uncertainties. Attempts can be made in order to estimate future failure rates and degradation rates, but there will always be uncertainty connected to our estimates. Information such as rationale, assumptions and confidence levels behind uncertain values are lost during the modelling process and therefore impair the decision making process.

If a large and relevant database is available, the probabilities derived from it could be precise in the sense that they may be able to provide accurate predictions of future events. But in risk analyses the focus is often put on rare events, so called tail events – events which catches one by surprise and often has severe consequences (Aven 2008).

Uncertainty management and safety management seek to produce more desirable outcomes, by providing insights about the uncertainties relating to the future possible consequences of a decision, and controlling and reducing these uncertainties. In quantitative risk analyses, most approaches to treatment of uncertainty seem to be based on the thinking that uncertainty relates to the calculated probabilities and expected values. This causes difficulties when it comes to communicating what the analysis results mean, and could easily lead to weakened conclusions if large uncertainties are involved. In a qualitative or semi-quantitative analysis, a more comprehensive risk picture can be established by taking into account the underlying factors influencing risk.

Selvik, Scarf et al. (2010) argues that probabilities and expected values do not alone serve the purpose of the risk assessment, to reveal and describe the risks and uncertainties, as a basis for risk-informed decision-making. The full scope of the risks and uncertainties cannot be transformed into a mathematical formula. There is a need to look beyond the probabilities – subjective or not – to allow for the assistance that the outcomes of the risk assessment and uncertainty analysis provide decision makers. The main benefit of adding uncertainty analyses is the improved ground for making decisions regarding risks. A clearly informed picture of the problem is in fact the bottom line concern in decision making – in order to make a well-put

decision a clear and informed picture of the problem must be presented in which decision makers can confide in and reason with (Aven and Zio 2011).

3.3 FRAMEWORK

In this section a descriptive presentation and explanation of the ERBI framework is given. The framework is divided into two sections, where the first part includes the steps from the normal RBI method and the second part introduces the extension, the ERBI, developed by Selvik, Scarf and Aven (2010).

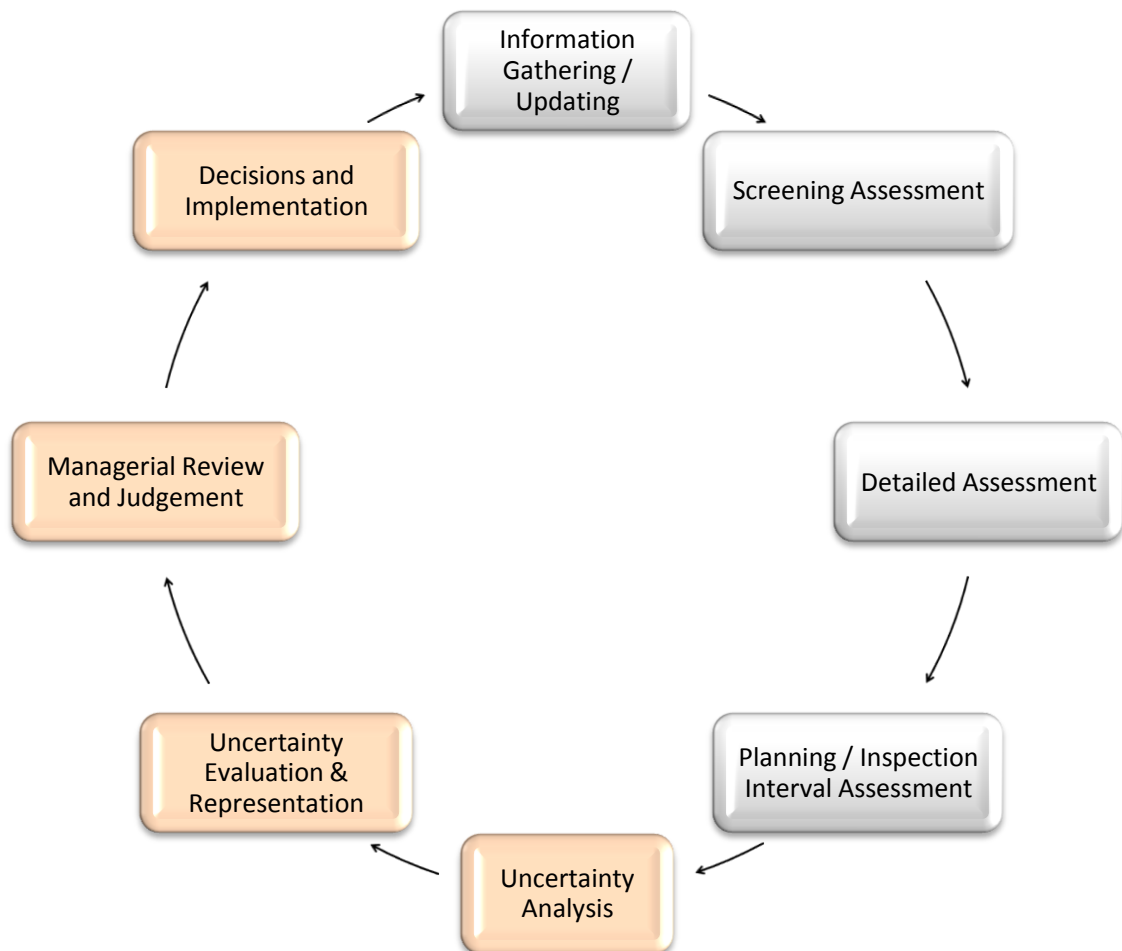


FIGURE 8 ERBI FRAMEWORK

The figure covers the entire RBI framework – information gathering, screening assessment, detailed assessment and planning/inspection interval assessment - with additional phases in order to assess the uncertainty. The additional steps, the extension, in ERBI are highlighted in the figure. Together they comprise the complete ERBI Framework. All phases will be described in this chapter, followed by a recommended method of practice in chapter 4. The first four phases are very much similar to the common RBI framework and based on the recommended practice by DNV (DNV 2009) and on the description of the ERBI methodology (Selvik, Scarf et al. 2010).

3.3.1 INFORMATION GATHERING

During the information gathering phase, general information about the system under inspection is collected with the object of revealing as much information possible about expected lifetime, current and future failures and failure modes, possible consequences and expected downtime.

Relevant information may be found in a number of different ways. By taking a closer look into the equipment list, one will be able to find data sheets that will provide much of the basic information about the different items/components in the system. Further information about failure rates can be collected from data bases based on historical events from similar or identical equipment.

3.3.2 SCREENING ASSESSMENT

Screening of the equipment is performed in order to discover critical data, i.e. parameters that directly have a significant negative influence on the frequency of the system down time. Potential hazards, threats and other risk influencing factors should be in focus during all screening phases.

In the process of identification of failure modes, FMEA or similar analyses are recommended. The FMEA can however be a time consuming process. Here, manageable units should be applied in accordance with the Level Hierarchy mentioned earlier. As this phase is simply a screening phase, there is no need for a very detailed assessment and hence only the top- to mid-levels are relevant.

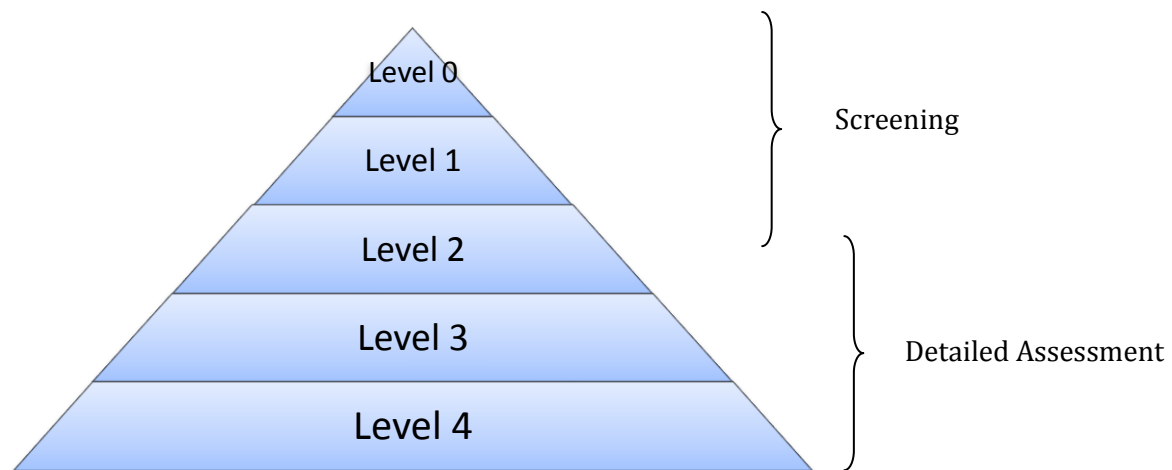


FIGURE 9 EQUIPMENT LEVEL HIERARCHY (DNV 2009)

Level 0 is the top level and covers a very wide spectre. If assessing a subsea installation, level 0 can equal the entire field as a whole or even tie in relevant connections to other fields. Information about materials and design are needed in order to evaluate failure modes at this level. Also personnel involved need to be considered and documented. Level 0 is a rough assessment, and does not go into any details or particularities.

Level 1 constricts to a particular system within the field assessed in Level 0. The objective of the assessment in this level is the identification of systems which may contribute negatively to the overall risk level.

Level 2 is used to reveal groups within a system which can be characterised as critical. This is typically groups of components that are to be found within the different systems.

Not all levels are needed or appropriate to use, depending on the situation. In cases where relevant data or applicability of the levels is lacking, fewer levels can be used as long as the principle of starting in a wide spectre and narrowing down is applied. The level hierarchy is a simple method of saving time when assessing a potentially big and complex system or field.

3.3.3 DETAILED ASSESSMENT

At this stage it is recommended to work at level 2, 3 and 4 in the Equipment Level Hierarchy.

Level 3 is a further breakdown from level 2, where parts of a system are analysed separately. This level is quite time consuming, and it is important to keep track of all different parts and make certain that nothing is overlooked.

Level 4 refers to the inspection point level and is only carried out for inspection points of particular concern.

Based on our findings in the screening assessment and the information collected, all medium and high risk assets are investigated further by assessing PoF and CoF for each of the items as well as estimating the degradation- and damage rates.

Degradation of a component can consist of several mechanisms - individually or combined. It is preferred to be aware of all or as many as possible outcomes and combinations of degradation parameters. Many generic data bases contain PoF for several components. The calculation of PoF can alternatively be carried out by using Monte Carlo simulation or the First Order Reliability Method (FORM). There also exist several software tools created in order to calculate PoF.

The failure rates can be described either qualitatively or quantitatively, depending on data availability and situation, and can be categorised by the following system, based on DNV's recommended practice:

TABLE 2 PROBABILITY OF FAILURE DESCRIPTIONS (DNV 2009)

| <i>Category</i> | <i>Quantitative</i> | <i>Qualitative</i> | <i>Description</i> |
|-----------------|------------------------|--------------------|---|
| 1 | $>10^{-2}$ | Expected | - Failures can be expected annually in a small population - Failure has occurred several times a year in location |
| 2 | 10^{-3} to 10^{-2} | High | - Failures can be expected annually in a large population - Failure has occurred several times a year in operating company |
| 3 | 10^{-4} to 10^{-3} | Medium | - Failures may occur during installation - Failure has occurred in operating company |
| 4 | 10^{-4} to 10^{-5} | Low | - Failures may occur during installation - Failure has occurred in industry |
| 5 | $< 10^{-5}$ | Negligible | - Failure is not expected - Failure has not occurred in industry |

After the assessment of PoF and CoF, we look at Risk of Failure, RoF. RoF is equal to the PoF multiplied by CoF. The DNV recommends a risk matrix for visualisation, see table 1.

3.3.4 PLANNING / INSPECTION INTERVAL ASSESSMENT

The risk matrix is used further when planning the inspection intervals. The critical components will normally be in need for a more frequent inspection interval compared to the insignificant or minor risks. The risk matrix shows clearly which item is the most and least critical and is therefore of significant contribution.

The inspection interval assessment is based on a risk decision matrix which shows the recommended time between intervals:

TABLE 3 EXAMPLE OF RBI DECISION RISK MATRIX (DNV 2009). RECOMMENDED TIME BETWEEN INSPECTIONS (IN YEARS).

| | CoF ranking | | | | |
|---------------------|---------------|--------------|--------------|--------------|----------------|
| PoF ranking | Insignificant | Minor effect | Local effect | Major effect | Massive effect |
| $>10^{-2}$ | 0 | 4 | 2 | 1 | 1 |
| $10^{-3} - 10^{-2}$ | 0 | 4 | 2 | 1 | 1 |
| $10^{-4} - 10^{-3}$ | 0 | 0 | 4 | 2 | 2 |
| $10^{-5} - 10^{-4}$ | 0 | 0 | 8 | 4 | 4 |
| $<10^{-5}$ | 0 | 0 | 8 | 8 | 8 |

3.4 ADDITIONAL STEPS FOR THE ERBI FRAMEWORK

This section gives the reader a framework and recommended practice of the steps which are new to the RBI. When added to the existing RBI as described above, the following section encloses the entire framework for Extended Risk Based Inspection planning.

3.4.1 UNCERTAINTY ANALYSIS

The uncertainty analysis is an assessment of the uncertainty factors connected to the previous phases of the ERBI framework.

Uncertainty analyses cover the following main tasks (Selvik, Scarf et al. 2010):

- Identification of uncertainty factors
- Assessment and categorisation of the uncertainty factors with respect to degree of uncertainty
- Assessment and categorisation of the uncertainty factors with respect to degree of sensitivity
- Summarisation of the uncertainty factors' importance

The main tasks are based on Aven (2008) and follow a semi-quantitative approach of analysing uncertainties. Calculations of quantitative measures, e.g. PLL, FAR, etc., often requires a lot of resources and can be very time consuming and results in an estimate believed to be the most accurate compared to the real world. This estimate does however not necessarily reflect the world, and will in most cases prove to be more or less erroneous. The need to fit large risk pictures and uncertainties into simple numbers and calculations is a common mistake in the search for easily understandable, objective numbers.

The next step is to rate all uncertainties. Degree of uncertainty shall be categorised in the following table by whether one or more of the following descriptions are suited to the situation, based on Flage and Aven (2009) and Selvik, Scarf et al. (2010).

TABLE 4 DEGREE OF UNCERTAINTY (FLAGE AND AVEN 2009)

| Uncertainty | Description |
|---------------|--|
| Low | <ul style="list-style-type: none"> - The assumptions are seen as very reasonable - Much reliable data are available - There is broad agreement/consensus among experts - The phenomena involved are well understood; the degradation models used are known to give predictions with the required accuracy |
| Medium | <ul style="list-style-type: none"> - The assumptions are seen as somewhat reasonable - Some reliable data are available - There are variations in the consensus of experts - The phenomena involved are well understood, but the degradation models used are simple/crude |
| High | <ul style="list-style-type: none"> - The assumptions made represent strong simplifications - Data are not available, or are unreliable - There is lack of agreement/consensus among experts - The phenomena involved are not well understood; degradation models are non-existent or known/believed to give poor predictions |

The same categorisation is also to be performed for the sensitivity:

TABLE 5 DEGREE OF SENSITIVITY (FLAGE AND AVEN 2009)

| Sensitivity | Description |
|---------------|--|
| Low | <ul style="list-style-type: none"> - Unrealistically large changes in base case values needed to alter the outcome - Low degree of uncertainty |
| Medium | <ul style="list-style-type: none"> - Relatively large changes in base case values needed to alter the outcome - Medium degree of uncertainty |
| High | <ul style="list-style-type: none"> - Relatively small changes in base case values needed to alter the outcome (e.g. exceeded risk acceptance criterion) - High degree of uncertainty |

The uncertainty- and sensitivity factors' grading (low, medium or high) are scores of how significant the particular components are in relation to the entire system.

A summarisation of these factors' importance is performed. The importance is the average of the score from the uncertainty and sensitivity.

3.4.2 UNCERTAINTY EVALUATION & REPRESENTATION

All of the steps as explained above provide input to the uncertainty evaluation of the system studied. These results shall be presented to the management and create the basis for the decision making process.

3.4.3 MANAGERIAL REVIEW AND JUDGEMENT

The inputs from the various assessments are here presented to the management where they are placed into a broader context. Boundaries and limitations of the various assessments are taken into account, and also additional aspects and inputs are taken into consideration.

During the managerial review and judgement, alterations, revisions or analytical changes may be requested.

4. ERBI - RECOMMENDED PRACTICE

This chapter includes a proposal of recommended practice for the ERBI. A number of measures and guidelines which will make the methodology more comprehensible and effective will be presented in the following. The chapter will also give an idea of the workload needed to successfully perform and execute the ERBI method. Some of the potential pitfalls and mistakes are also discussed.

4.1 INFORMATION GATHERING

One of the most popular failure rate databases in Norway is the OREDA database, published regularly by DNV. OREDA stands for “Offshore Reliability Data” and presents a detailed statistical analysis on many types of process equipment. A number of other data sources exist as well, for example:

1. FMD-97, Failure mode / Mechanism Distributions, 1997, Reliability Analysis Centre, Rome, NY
2. Guidelines for Process Equipment Reliability Data, with Data Tables, 1989, Centre for Chemical Process Safety of AIChE, New York, NY
3. NPRD-95, Nonelectronic Parts Reliability Data, 1995, Reliability Analysis Centre, Rome, NY
4. IEEE Std. 500, IEEE Guide To The Collection and Presentation Of Electrical, Electronic, Sensing Component, And Mechanical Equipment Reliability Data For Nuclear-Power Generating Stations, 1984, IEEE, New York, NY
5. Reliability Data for Control and Safety Systems, 1998, SINTEF Industrial Management, Trondheim, Norway

(Goble 2002)

Common for all the databases are that the less specific data turns out to be, the more conservative are the corresponding numbers. This is according to the safety verification principle which states that “the less one knows, the more conservative one must be.”

These numbers should be used with care and with awareness of the variations in the calculations. Use of generic data should always be supplied – if possible – with installation specific data. This can be in the form of layout drawings, Process Flow Diagrams, Piping and Instrumentation Diagrams, Fabrication and Installation resume material design specification report, etc.

Expert judgement can be considered as an informed assessment or estimate about an uncertain component or system. Based on the experts training and experience, good information about most systems can be provided as addition to the database information. The expert should be capable of expressing useful opinions, either quantitatively or qualitatively or both, be aware of uncertainties in the opinions – overconfidence can lead to misleading judgements. Where different experts are used, it may prove an advantage to have experts looking at the problem from different points of view.

Additional interactions between QRA, RBI, RCM and other risk analyses are important to ensure consistency in relevant failure rates and associated downtime pattern for equipment covered in these analyses. When ensuring information flow between these analyses, efficiency and accuracy can be improved. Results from an early phase QRA may very well contain relevant information

for the ERBI. Regularity and availability data is also important to ensure a realistic interaction between the analysis and assets involved. Experiences of ERBI undertaken in the operating phases may also be utilised in connection with regularity analysis of design alternatives in the planning stages as well as in early maintenance planning (NORSOK 1998).

A Quantitative Risk Analysis (QRA) is often performed during the FEED (Front-End Engineering and Design) phase of the project. FEED is conducted after completion of Conceptual Design or Feasibility Study. At this stage, before start of E.P.C (Engineering, Procurement and Construction), various studies take place to figure out technical issues and estimate rough investment cost - amongst these are normally QRA studies. Sub activities of the QRA are:

1. description of concept
2. hazard identification
3. frequency calculations
4. consequence calculations
5. risk calculations
6. comparison of risk results with acceptance criteria
7. establishment of Emergency Preparedness Analysis

(Falck, Skramstad et al. 2000)

Examples of relevant information found in the QRA, are:

- risk elements
- fatality risk
- impairment risk
- barrier elements
- sensitivity analyses

Risk elements include factors of personnel, environment and assets. In the QRA report these should be noted and commented which reveal many additional failure modes to be used in the ERBI. Fatality risk is usually represented quantitatively by the parameters PLL, FAR, AIR and/or group risk (f-N diagram). Asset risk is normally presented in two dimensions; material damage risk and production delay risk. This will simplify our calculations of personnel safety CoF and economic CoF respectively. Impairment risk is related to the main safety functions, e.g. impairment of escape ways in a platform. Barrier functions, systems and factors are mentioned in the QRA report. These will in some cases lead to reduced PoF of certain components and/or systems. The sensitivity analysis is somewhat similar to the uncertainty analysis in the manner that assumptions and possible variations in relation to the previous calculations are assessed. The sensitivity analysis shows the effect of altered input parameters/values, which allows one to see how sensitive the calculations are to changes in assumed input parameters and hence see the level of importance of assumptions and suppositions (Vinnem 2007).

During the design and planning phase HAZOP/HAZID studies are commonly executed with the objective of identifying weaknesses and hazards. The study documents deviations, causes, consequences, recommendations and decisions. If particularly critical elements are discovered, more extensive analyses are usually performed. If well documented, the resulting conclusions of these analyses can make the ERBI screening assessment much more effective, as many of the potential failure modes and critical items are already discussed.

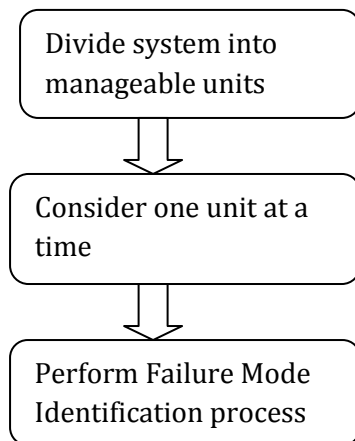
If knowledge about one or several of the components or systems are lacking, it is important to clearly define the real origin of lack of knowledge. In several cases it is also recommended to introduce experts to provide useful information in forecasting and assessing risk, e.g.:

- If data are sparse or difficult to obtain. Sometimes information is not available from historical records, prediction methods or literature.
- If data are too costly to obtain.
- If data are open to different interpretations, and the results are uncertain (unstable).
- If models to analyse risks are not available.

(Daneshkhah 2004)

4.2 SCREENING ASSESSMENT

The following working process in this stage is recommended:



In the case of unreliable or not applicable estimates, expert judgements should be introduced along with the necessary assumptions. In cases where the outcomes of an event are highly uncertain along with unknown probabilities, the precautionary principle should be applied. It is particularly important that all uncertainties and additional assumptions and limitations are noted as these are to be further assessed in the uncertainty analysis.

Beyond this the reader is referred to DNV's recommended practice (DNV 2009) which provides a good description of the performance of both the screening assessment and the detailed assessment.

4.3 DETAILED ASSESSMENT

The Consequence of Failure, CoF, is best described in a qualitative manner for safety and environmental risks, and is basically an outcome of the failure modes identified in the screening. Consequences are normally defined in the FMEA process, and so evaluations, embellishment and descriptions are necessary in order to find the level of criticality. Re-use of other relevant analyses like QRA's, is recommended.

Consequences of Failure are usually divided into three types of consequences:

- safety (CoF_{safety})

- environment ($\text{CoF}_{\text{environment}}$)
- economic ($\text{CoF}_{\text{economic}}$)

The consequences can be categorized by using the following examples of classification system:

TABLE 6 COF SAFETY

| Consequence class | Description |
|-------------------|--------------------------------|
| 1 | Fatalities |
| 2 | Permanent injuries |
| 3 | Injury with hospital treatment |
| 4 | Injury |
| 5 | No injury |

TABLE 7 COF ENVIRONMENTAL

| Consequence class | Description |
|-------------------|--------------------------------|
| 1 | Serious Damage |
| 2 | Damage, no mitigation possible |
| 3 | Damage, mitigation possible |
| 4 | Minor damage, mitigation easy |
| 5 | No damage |

TABLE 8 COF ECONOMIC

| Consequence class | Description (\$) |
|-------------------|------------------|
| 1 | < 250.000 |
| 2 | 50.000 – 250.000 |
| 3 | 10.000 – 50.000 |
| 4 | 5.000 – 10.000 |
| 5 | 0 – 5.000 |

Note that these are only examples and may therefore not be relevant for all businesses or projects as the criticality of the consequences can be experienced very different (perhaps especially with regards to economic consequences).

When assessing the costs, it is particularly important to include all aspects – both direct and indirect, e.g. direct losses from production shut down versus indirect loss due to reputational damage. The following model can be used (Heerings and den Herder 2003):

$$\text{CoF}_{\text{Economic}} = C_{\text{LP}} + C_{\text{PC}} + C_{\text{SC}} + C_{\text{Id}}$$

Where:

- C_{LP} = cost of Lost Production
- C_{PC} = cost of Primary failure
- C_{SC} = cost of Secondary failure
- C_{Id} = indirect costs.

Relevant information and data may be more or less accurate. A few examples of the outcomes and approaches to problems arising from the gathered data and assessment are listed:

- The outcome is clearly defined, and its occurrence is firmly established on solid statistical ground
- The outcome is clearly defined but probabilities estimates can hardly rely on statistical data because situations under concern are not generic enough
- No probability estimate is applicable
- Probabilities are known to a certain degree but the outcome of the event is poorly defined
- Both probabilities and outcomes lack clarity

(Giribone and Valette 2004)

A numbered standard 5x5 matrix is recommended, as shown in the table below:

TABLE 9 NUMBERED RISK MATRIX

| CoF PoF | 5 Insignificant | 4 Minor | 3 Local | 2 Major | 1 Massive |
|------------------------------------|---------------------------|-------------------|-------------------|-------------------|---------------------|
| 1 $>10^{-2}$ | 2 | 2 | 1 | 1 | 1 |
| 2 10^{-3} to 10^{-2} | 3 | 2 | 2 | 1 | 1 |
| 3 10^{-4} to 10^{-3} | 4 | 3 | 2 | 2 | 1 |
| 4 10^{-4} to 10^{-5} | 5 | 4 | 3 | 2 | 2 |
| 5 $< 10^{-5}$ | 5 | 5 | 4 | 3 | 2 |

From the matrix we deduce which events and components are the most critical (red), and which ones may be accepted or do not require that much attention (green). The numbers represent similar levels as for the CoF and PoF. Components or systems containing risk levels higher than what is accepted need to be considered replaced or have additional risk reducing measures implemented. This is assessed further in the process.

There exist different methods for deciding which level is acceptable, e.g. risk acceptance criteria and the ALARP principle. Here, a combination of both is recommended. Whereas the acceptance criteria create clearly defined upper limits for what is accepted, the ALARP principle states that the risk should be reduced to a level as low as reasonably practicable. In practice this means that the risk must be lower than the predefined acceptance limit, but should in most cases be further reduced. Because the ALARP principle is not a clear line, confusions about what is reasonably practicable or not, may occur. The additional risk acceptance criteria will ensure an upper risk limit where, however impracticable, the risk has to be reduced. In certain cases this will lead to new and improved solutions, components, etc. which may or may not have been discovered by solemnly applying the ALARP principle. However, the final decision of acceptance and

implementation of measures is ultimately made by the management during the last phase of managerial review and judgement.

4.4 PLANNING/INSPECTION INTERVAL ASSESSMENT

A recommended inspection plan should be the final outcome of this phase, which includes

- Clearly defined components and criticality
- Failure modes and damage/degradation rates
- Risk in relation to the risk acceptance criteria and ALARP
- Cost of inspection of the components / systems
- Concluding remarks
- Recommended inspection plan based on the above
- Additional recommendations of risk reducing measures

The preliminary inspection plan should also include inspection methods and examination frequency. The frequency should be consistent with the risk of system failure associated with a particular item, and be easily updated as new information is retrieved. When deciding on the periodicity between examinations, the aim should be to ensure that examinations are carried out at realistic frequencies to identify, at an early stage, any deterioration that is likely to affect the safe operation of the system.

The cost of inspections should also be included in this assessment. These estimates may also include more or less uncertainties in relation to the complexity of the inspection. Estimated prices can be gathered from the relevant contractors. LCC (Life Cycle Cost) is often used in the design process to evaluate the product cost over the total life span. The estimated cost of inspections can be looked at in relation to the LCC in order to reveal different aspects of the components and hence better be able to decide on the inspection interval.

4.5 UNCERTAINTY ANALYSIS

The analysis is created as an addition to the preliminary inspection plan in order to implement all uncertainties in relation to assumptions and simplifications in the final decision making.

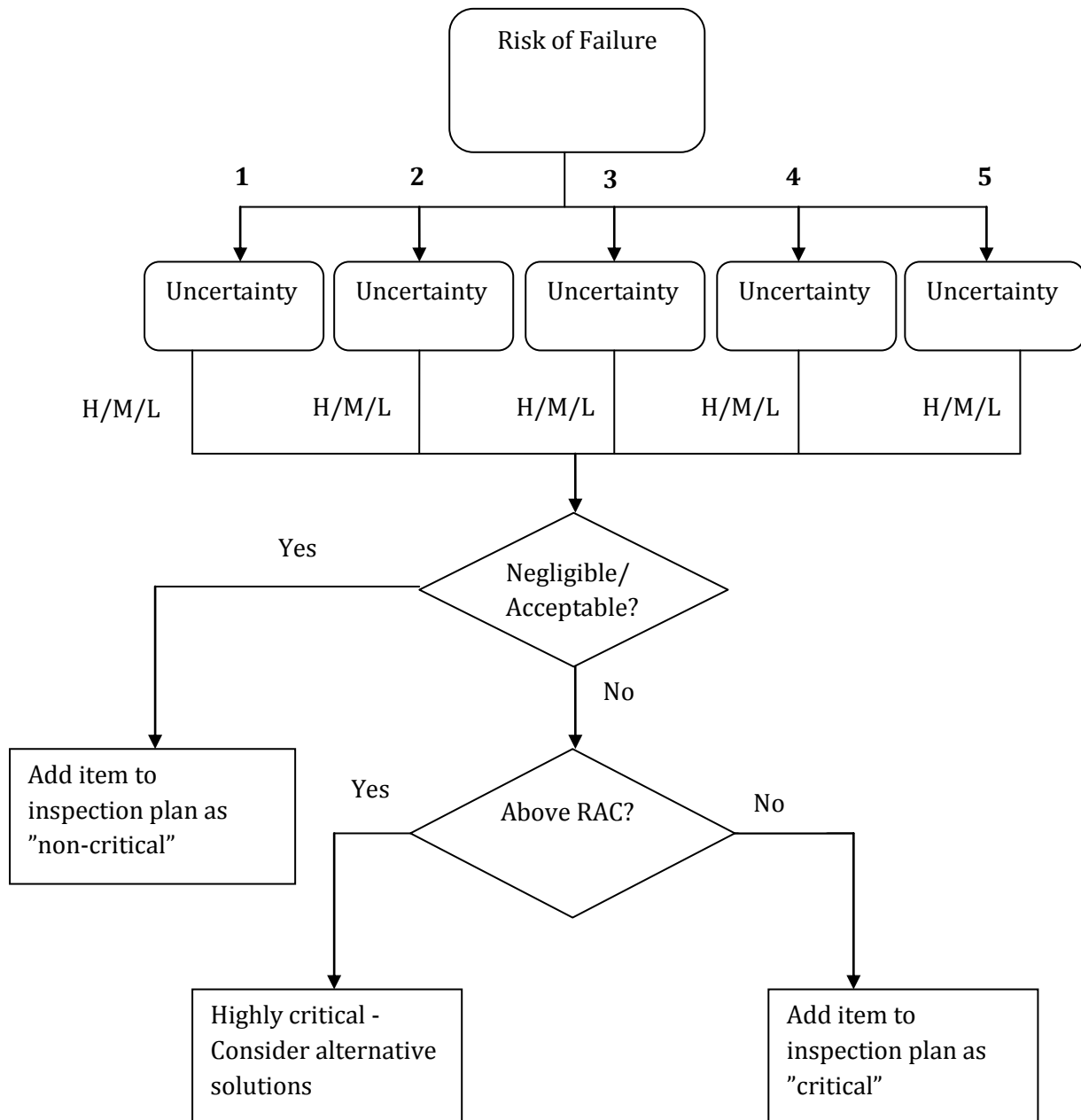
All assumptions, simplifications etc. made in the previous sections should by this phase have been noted, and hence be of significant attribution when indentifying the uncertainty factors. In securing that all uncertainty factors are accounted for, uncertainty can be split into three main sources:

1. Ignorance (inadequate understanding of situation)
2. Unpredictability (data are not existent or lacks reliability)
3. Ambiguity (in data and expert judgements)

By assessing all of these sources, one is more certain not to overlook any uncertainties.

A summarisation of risks and respective importance levels are gathered. This is documentation of all discovered risks including degree of severity, uncertainty and sensitivity. The level of importance divides the decision-relevant uncertainty - that is scientific uncertainty characterised by experts to be of use for decision-makers – from less relevant factors of minor importance to the system and RoF. In connection with ERBI the decision-relevant uncertainty is a subset of all uncertainties about the potential risks at issue. We can differentiate between

“critical” and “non-critical” items which need inspection and “highly critical” which must be considered altered more dramatically. The following actuation is proposed:



All risks (RoF) discovered in the earlier phases are here assessed with regards to uncertainty (High, Medium, Low) and with the risk acceptance criterion (RAC) as a final limit of what is accepted. RoF is to be seen in relation to the corresponding level of uncertainty and further rated under “non-critical”, “critical” or “highly critical”. An example of a non-critical item has for instance a RoF equal to 5 and Low uncertainty level. At the other end we have the highly critical items, e.g. RoF equal to 1 and High uncertainty level. The non-critical items are risks assumed to be tolerable; however this should be confirmed in the managerial review. Highly critical items are intolerable risks which need more drastic changes. All items follow the ALARP principle of lowering the risk to the lowest practical limit.

Risks should be seen in relation to a reference value – a value considered to be normal for the particular item. Depending on the situation, the result may vary with the situation as well as with the different RoF ranks and uncertainty levels.

4.6 UNCERTAINTY EVALUATION & REPRESENTATION

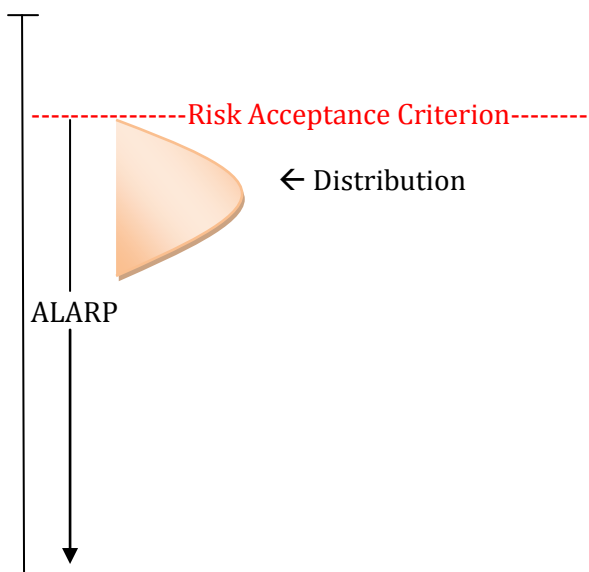
In the uncertainty evaluation, a broad uncertainty description is provided, covering probabilities and related background knowledge. In the representation of the results it is especially important that all results are presented in a way that makes the decision-maker understand all aspects. Unless this is the case, then the method dramatically loses its purpose.

When evaluating the risks a summary of each risk and additional uncertainty should be given. The thoroughness of the report depends on the criticality of the risk and uncertainty level and can be divided into the three groups:

- Non-critical
- Critical
- Highly critical

The report shall consist of a concise description of the item, followed by a written representation of the related sensitivity with a best and worst case scenario. Further it is stated whether the related uncertainty was found to be high, medium or low, with the criteria for each state clearly noted. A concise description of the background of the uncertainty, i.e. its origin, is to be given.

The estimates represented should be expressed in terms of distributions rather than as point estimates. This is because the calculations are not exact predictions of the future and may vary widely. There is also a natural aleatory uncertainty within all numbers which should be accounted for. By presenting distributions, it is made clear that the outcome is not expected to be the exact estimate but rather a number which may vary, although earlier calculations of PoF and RoF show the result we believe is most likely. The figure below shows how this works in relation to the risk acceptance criteria and the ALARP principle.



Note that such distributions should be used with great care as they do not provide a full and ideal risk picture. It does not include tail-events, e.g. surprises which are unaccounted for, and should therefore only be used as a visual aid – not a complete representation!

An expansion of the earlier performed risk matrix can also be used as visualisation of the uncertainties in relation to the risk of failure. A bubble matrix can be used, where the size of the bubbles equals the uncertainty related to the component or system.

TABLE 10 BUBBLE RISK/UNCERTAINTY MATRIX

| CoF PoF | 5 Insignificant | 4 Minor | 3 Local | 2 Major | 1 Massive |
|------------------------------------|---------------------------|-------------------|-------------------|-------------------|---------------------|
| 1 $>10^{-2}$ | | | | L | |
| 2 10^{-3} to 10^{-2} | | | | | |
| 3 10^{-4} to 10^{-3} | | | | | |
| 4 10^{-4} to 10^{-5} | | H | | M | |
| 5 $<10^{-5}$ | | | | | |

This method for representation of uncertainty also allows for the visualisation of cases where high uncertainties not necessarily have a big impact on the risk level and vice versa.

The sensitivity is recommended visualised in a traditional tornado chart with the risk acceptance criterion and reference value included. Alternatively the radar chart also depicts the sensitivity sufficiently.

The figure underneath shows a crude example of how the simplified results may be presented in a report.

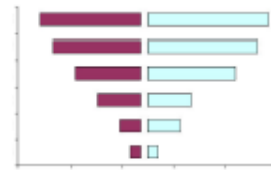
RISK DESCRIPTION

Corrosion damage to pipelines

- The pipelines are to transport gas condensate
- Depth: 200 m.
- Length: 1,2 km.
- Life span: 20 years
- Material used: stainless steel
- Corrosion inhibitors are in place

SENSITIVITY

- Best case scenario involves no corrosion for the entire calculated life expectancy of the system
- Worst case scenario involves a large crack extending over a significant area of the pipeline, causing a full production stop.



UNCERTAINTY

Overall uncertainty level has been found to be **Medium**, based on the following:

Assumptions:

- Calculated production: 300-450 boe/day
- Calculated pressure: 110-120 bara
- Planned regular maintenance every 3 years

Uncertainties:

- Expected life span: 25 years
 - Uncertainty level: Low
 - Generic data from similar installations
- Expected need for maintenance: every 3 years
 - Uncertainty level: Medium
 - Based on expert judgment

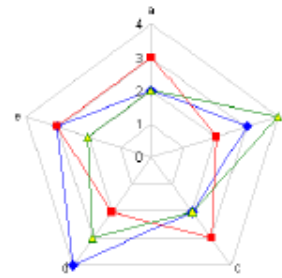


FIGURE 10 PRESENTATION OF RESULTS

In addition there should always be further available documentation, if needed, from earlier phases, of all

- Risk drivers and corresponding risk levels
- Uncertainties and corresponding uncertainty levels
- Sensitivities and corresponding sensitivity levels
- Assumptions and use of databases and expert judgements

4.7 MANAGERIAL REVIEW AND JUDGEMENT

Management involvement is strongly advised throughout the entire assessment, however, at this stage all results are gathered to provide the basis for making appropriate decisions. The management reviews inputs from all available assessments, inputs from manufacturers, existing maintenance/inspection programs and see the results with regards to boundaries and limitations.

As shown so far, the ERBI method contains premises, assumptions and limitations and therefore also need to be evaluated in the light of these. Strictly mechanical procedures for transforming the results of the assessments and evaluations to a decision cannot be justified. It is a management task to weight these uncertainties and risks, and balance the different concerns.

When evaluating the decision support the decision maker needs to consider a number of issues, including

- The process and documentation of results – if not satisfactory changes will be necessary
- The analysis' limitations
- Concerns not taken into account
- Costs versus risk
- Codes and standards
- Company or internal values
- Society values

Sometimes a new or different situation arises that might need, but has not been subjected to, sufficient public debate. In some of these cases great care is needed to try to assess society's views and expectations as part of the decision making process and these may affect what is seen as tolerable or reasonably practicable (Tope 1999).

4.8 DECISIONS AND IMPLEMENTATION

The preliminary inspection plan is by this point thoroughly reviewed and decision alternatives are to be implemented. Based on the preliminary inspection plan and in combination with the observations, judgements of the uncertainties and the managerial review, a final detailed inspection plan is ready to be presented.

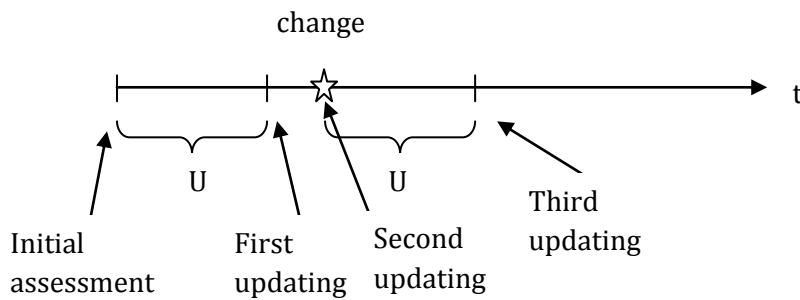
The proposed changes and how the implementation of changes is performed must be considered when evaluating the different decision alternatives. The effect of a decision alternative could undergo gradual change, the response of a measure could be different to what was expected, concerns may change etc. The decisions therefore have to be evaluated after implementation, to see how they perform relative to the challenges and problems they were supposed to meet. From this, modifications may be required in the updating of the inspection plan (Aven, Vinnem et al. 2007).

4.9 UPDATING

A good inspection program contains a plan of inspection which has the optimum time between inspections that result in the lowest annual cost. The ERBI should be reassessed regularly in order to provide the best possible data about

- Deterioration mechanisms and inspection activities
- Changes in the equipment / components

It is recommended that the reassessment is performed after any significant changes or after a predefined period in time. This is shown in the figure below where U represents a specific time period and the star is when a significant change in the system is made.



The reassessments should include severity and type of damage (if any) compared to the expectations in the inspection plan. If these show to be significantly different, a consideration of whether the ERBI results should be modified is recommended. All changes to the system or equipment will in most cases change the risk picture and hence this must be noted and included in the inspection plan. When updating an analysis (or using the analysis for further studies) all basis for the analysis should be reviewed.

When carrying out an inspection or any non-destructive measurement, one has to consider errors from measurements, instruments as well as other human errors. This means that there will be additional uncertainties included in the inspections and therefore also in the reassessment. This should be noted in the case of further needs for decision support.

At a certain point in time, the updating will no longer be valuable – the cost of inspections and ERBI assessments will be greater than what the system itself is worth if the expected lifetime is at an end and/or equipment is in its final period of use/operating phase. One needs to consider the extent of work and the time required to perform inspections and reassessments of analyses versus the need for decision support at a given time. If this is not clear in the initial inspection plan, it should become more evident throughout the system life cycle and will need assessment and additional decision-making.

5. VERIFICATION

This chapter discusses the verification assessment. A general explanation of the regulations in which the verification scheme must work in compliance with is necessary to understand in order to be able to perform the RBV method. This is provided in chapter 5.1, followed by the RBV framework in accordance with the DNV recommended practice in chapter 5.2.

The RBV method is believed to contain many similarities to the ERBI method, and hence time and resources can be saved by reusing information from the ERBI when performing RBV. In chapter 5.3 a number of potential improvements to the RBV practice are given, which have the intention of connecting the two methods into performing more unified with the common advantage of assessing the uncertainties.

5.1 REGULATIONS

The UK Health and Safety Executive (HSE) have a clear definition of the verification process in The Safety Case Regulations (2005). The Regulations implement the central recommendation of Lord Cullen's report on the public inquiry into the Piper Alpha disaster: that the operator or owner of every offshore installation should be required to prepare a Safety Case and submit it to HSE for acceptance. The Safety Case includes:

- Identification of the Major Accident Hazards
- Strategy for risk reduction
- Identification of safety critical elements
- Development of Performance Standards
- Assurance
- Independent Verification

The independent verification regulation firstly states that it is the duty holder's responsibility to ensure a record of the safety critical elements of an offshore installation. A third party is, in advance of the production phase, to perform the following:

- Comment upon the records
- Draw up a verification scheme, either solemnly or in cooperation with duty holder
- Ensure that the scheme is put into effect

The duty holder has the responsibility of ensuring that such a verification scheme is prepared, put into effect and maintained.

Essential to such a scheme is the identification of Safety Critical Elements (SCE) for the installation. Work done to identify hazards in preparing this safety case, will assist this process. The duty holder can chose to use a contractor for this work or own company. In any matter, the responsibility lies with the duty holder.

The duty holder shall ensure that the verification scheme is reviewed and revised or replaced by or in consultation with an independent party when necessary. The review and revision should be performed as often as appropriate throughout the installation's life cycle, as well as after changes and alterations which may have an effect on the outcome on the results of the verification scheme (HSE 2005).

Norway considers the acceptance of a Safety Case - or a similar documentation by the operator - as very time consuming, and is therefore not a requirement. However, the same risk assessment and description of how the operator intends to control identified risk is in fact required. These documented assessments must be available to the Norwegian government (Petroleum Safety Authority, the State Pollution Agency or the Health directorate) at any time. The operator can select individually to perform a Safety Case and have it verified by an independent body (Marty, Theys et al. 2010).

The Norwegian Petroleum Directorate has however specified the need for verification in Framework HES §19 where states that:

The responsible party shall determine the need for and scope of verifications, as well as the verification method and its degree of independence, to document compliance with requirements in the health, safety and environment legislation. When verifications are deemed necessary, they shall be carried out according to a comprehensive and unambiguous verification programme and verification basis.

The operator shall establish the verification basis for the overall activities after assessing the scope, method and degree of independence of the verification. The operator shall also carry out an overall assessment of the results of the verifications that have been carried out. (The Petroleum Safety Authority Norway 2010)

As stated above, a programme for verification must be in place in order to document compliance with the HES legislation. In order to secure compliance, the operator must carry out an overall assessment of the results of the verifications. This means that in the case where non-compliance is documented, it is the operator's responsibility to correct this. The verification should normally be executed by a third party with the necessary experience and resources, but this is not a requirement.

5.2 RISK BASED VERIFICATION

Risk Based Verification (RBV) is becoming increasingly popular in the offshore industry. The fundamental concept of a risk based approach is the development of a risk assessment to understand the risk contributions of each component within the scope, and then use this information to develop an installation specific verification scheme.

The DNV has created a framework for RBV which is based on (DNV 2004)

- Hazard identification
- Risk assessment
- Evaluation of risk-control options
- Recommendations for decision-making
- Development of a verification plan
- Performing verification according to plan.

The requirements of National Authorities are not included specifically in the scope of application. Note that some national authorities may have detailed requirements to the certification activity, while others leave the definition of the necessary work up to the appointed organization. Regulations vary from country to country, and where two or more countries are involved, both need to be considered. We find many examples of this in the North Sea, where

fields in the Norwegian sector are tied back to, and controlled by, UK platforms. The development must therefore comply with both sector's regulations. For example, the Norwegian concept of identifying barriers and minimising the pollution to the marine environment does not exist in the UK (Marty, Theys et al. 2010).

The DNV framework is divided into five phases (DNV 2004):

1. **Asset Specification:**
 - Hazard identification
 - Verification objectives
2. **Risk assessment:**
 - Categorisation of risks
 - Probability assessment
3. **Definition of verification involvement:**
 - Acceptance criteria
 - Performance requirements
4. **Verification Plan:**
 - List of verification activities
5. **Verification execution:**
 - Reporting of compliance or non-compliance.

As the method is very general, it can be applied at different projects and systems. A less specific verification plan can cause more work, but will by completion in general turn out to be more specific compared to specified verification plans. New technology, different setting and so on, makes even the specified verification plans unspecific, at the same time as it can give a false sense of security.

Regular assessments will be carried out to confirm that any deterioration of the system is within acceptable limits and that the system continues to be fit for its intended purpose, in accordance with the inspection/maintenance plan. The verification plan is on the other hand in place to assure that this is in fact the case, and that the system operates safely, as intended and in accordance with the rules and regulations in force for that particular system/field.

5.3 PROPOSED IMPROVEMENTS TO RBV IN RELATION TO ERBI

It is evident that the RBV methodology has many similarities to the RBI. Common practice in industry is that these two steps are fairly connected, although performed separately. When the performance of the two integrity management methods are seen and executed more as one, a significant amount of the work can be avoided duplicated.

The assessment of uncertainties in the ERBI methodology should also be included in the RBV assessment, in order to make sure the assumptions made in the HAZID, risk assessment etc. is accounted for, and hence presents a decision basis beyond the calculations of expected values and estimates. In the same manner as for the extension of RBI, the additional uncertainty analysis will improve the grounds for decision-making.

This methodology is based on a general verification plan secondary to the execution of the Extended Risk Based Inspection method. It is therefore necessary to complete the ERBI first, in order to retrieve all relevant data for the verification of the system.

From the ERBI assessment we already have several of the above points defined and assessed:

- A clear definition of risks with related consequences and probabilities
- Categorised high, medium and low failure modes
- Uncertainty analysis
- Categorisation and evaluation of the uncertainties
- Management's point of view on risks and uncertainties and related requirements to performance

Hence, when connecting the two assessments of ERBI and RBV, i.e. use the already gathered information from the ERBI, we get a simplified and less time consuming framework:

1. Gather information from ERBI:

- Failure modes
- Uncertainty evaluation and representation

2. Define level of verification and objectives:

- Look at Risk Acceptance Criteria from ERBI
- Use notes from the managerial review and judgement in ERBI

3. Verification plan:

- Based on the above, list the verification activities needed to keep the system functioning
- Set a proper time scale for the verification, related to the inspection plan

4. Execute verification plan:

- Report of compliance or non-compliance

The failure modes and uncertainty evaluation and representation creates the basis for some of the decisions to be made with regards to which objects need more or less focus than others. The failure modes show the different scenarios for what may cause system failure. These modes may contain several smaller components which otherwise may not have been assessed. The uncertainty evaluation and representation clearly define high-, medium- and low risk objects with regards to the respected uncertainty, which should describe the total risk picture and give a good idea about the most critical items.

The selection of the level of verification should depend on the risk level of each element having an impact on the management of hazards and associated risk levels of the asset. The risk acceptance criteria are in ERBI used as a maximum limit for risk acceptance. It is therefore not necessarily ideal to be at a risk level at this point or just below. In the ERBI assessment the ALARP principle was also used in order to push the risk level to its optimal state. Hence, to create an acceptance limit for the verification, it is also necessary to look at the managerial review and judgement for what risk level is in fact desired. This may or may not be different from the risk acceptance criteria. The objective of the verification plan is defined on the basis of the managerial judgements on the risk levels and uncertainties, and in combination with the third party's agreement regarding risk levels and verification limit. It is here defined what the verification is to cover and the extent of accuracy needed.

The verification plan is a summary of the above, with a list of items due to inspection. It covers the project's design, manufacturing, installation and commissioning based on the predefined risk level. The verification plan should be reviewed and approved prior to the production work.

The final inspection report should cover all aspects of the third party's inspection work according to the verification plan. The release notes are to be issued upon completion of each manufacturing, installation as well as commissioning activities. The release notes are based on the following:

- Inspection reports
- Non-conformance reports and their rectifying actions
- Final documentations

Common practice is also issuing a Certificate of Conformity upon completion of all verification work.

PART II:

CASE: THE “TRYM” SUBSEA INSTALLATION

6. THE TRYM FIELD

Trym is located in the Norwegian sector of the North Sea, immediately north of the Danish/Norwegian boundary, 250 km south-southwest of Egersund. It is a subsea tie-back to the Maersk Harald platform 5 km southwest of Trym, crossing the Danish border.

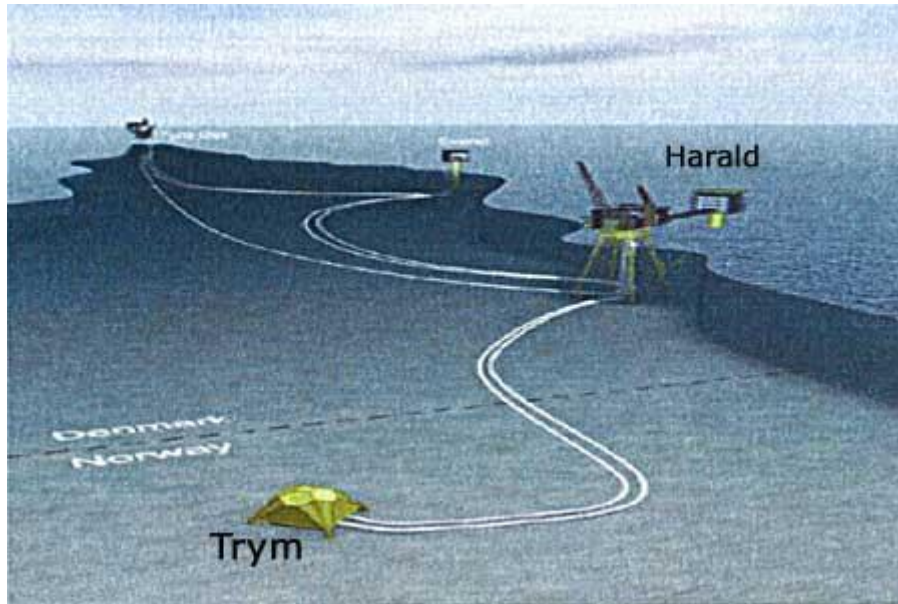


FIGURE 11 THE TRYM FIELD (ACERGY/BUREAU VERITAS)

It is a gas condensate production well with a production potential of 2.1M Sm³ per day. The development is in the form of a subsea installation with two horizontal wells that are tied back to and controlled from Harald. Producible reserves are estimated to 3.3 billion Sm³ gas and 0.8 million Sm³ condensate.

The project was awarded the client, Dong Norway, in May 2009, with plans of offshore operations by the second quarter of 2010 and first gas production by the fourth quarter of 2010.

Key data (obtained from notes by Acergy given to Bureau Veritas):

- Water depth: 65 metres
- Design life: 20 years
- Design pressure: 380 bar
- Design temperature:
 - High 120°C
 - Low -45°C
- Diverless

There is also a sour service requirement related to the pipe lines. Natural gas containing hydrogen sulphide, H₂S, is generally referred to as “sour gas”. When low-alloy steel corrodes in an aqueous solution containing hydrogen sulphide, it may suffer hydrogen assisted damage. Damages in the form of cracks, internal cracks and surface blisters have been reported ever since the production of gas condensate containing hydrogen sulphide started. Hence, test requirements for hydrogen induced cracking (HIC) are introduced (Schroder, Schwinn et al. 2006). The H₂S partial pressure might also influence the material selection. Hence, solid

corrosion resistant alloys (CRA) or clad will be utilized when risk for corrosion attacks exists. Different types of steels have earlier been used as pipes, castings, forgings and small bore tubing. In general the experience is good but some significant failures have occurred. The main reason for these failures has been attributed to an unfortunate combination of load/stress and hydrogen embrittlement (HE) caused by ingress of hydrogen formed at the steel surface due to the cathodic protection (Gryttena, Nilsson et al. 2007). This is called Hydrogen Induced Stress Cracking (HISC) and is included in the key data in the design of the Trym project.

The Trym field consists of the following main elements:

- SPS template and manifold system
- Flexible flow line
- Heating spool
- Umbilical
- CPI's
- Remote tie-in systems (RTS)

The main interfaces are

- The Harald platform (including riser caisson system)
- SPS manifold and tie-in system
- Umbilical

The Trym field is located in the Norwegian part of the Søgne basin north of the Lulita field. Trym is considered to be separated from the Lulita field, but with possible pressure communication in the water zone (Petersen and Brekke 2001).

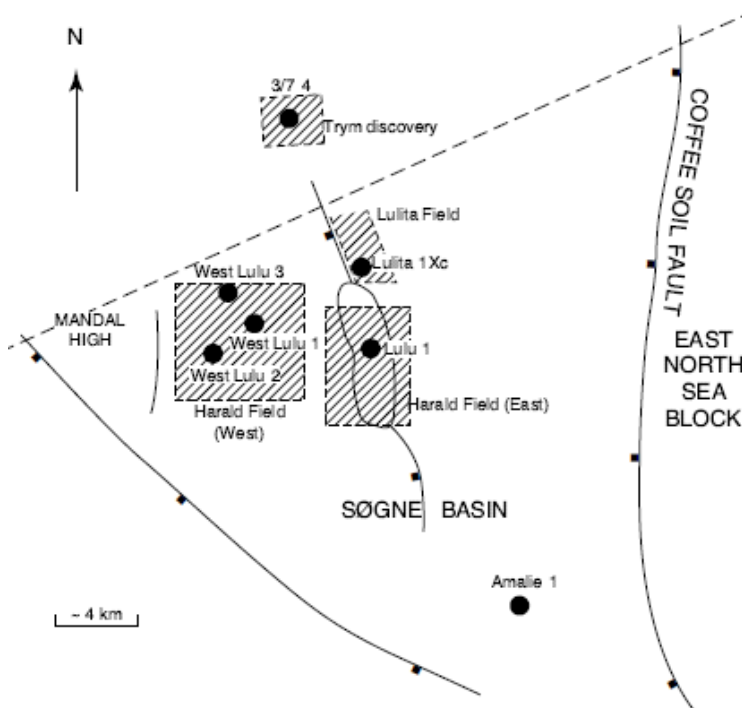


FIGURE 12 SØGNE BASIN (PETERSEN & BREKKE, 2001)

7. EXTENDED RISK BASED INSPECTION FOR TRYM

7.1 UNCERTAINTY ANALYSIS

When looking at relevant data of the Trym subsea installation with regards to uncertainties, we focus on any factors which may have potential of affecting the inspection intervals. Such factors normally exist where assumptions and shortcuts have been made during several of the projects phases. Some of the most obvious findings are reviewed and commented upon in the following sections.*

7.1.1 THE “LAVRANS-SHORTCUT”

The design brief makes clear that the Trym field shares so many similarities to another field called Lavrans, that much of the data and work has not been performed uniquely for Trym. Such shortcuts can save a lot of time and expenses, but it is extremely important to keep track of all assumptions made by deciding to re-use data from another installation.

The Lavrans reservoir is located in the Haltenbanken area of the Norwegian Sea, approximately 5-10 kilometres south of the Kristin platform and 220 kilometres offshore Mid-Norway, see figure below.



FIGURE 13 LOCATION OF LAVRANS FIELD (STORVOLL, BJØRLYKKE, KARLSEN, & SAIGAL, 2002)

The water depth at the sight varies between 270 and 280 metres. The reservoir is subject to a large overpressure of approximately 900 bars and with a reservoir temperature of 160-170 degrees C. Both the Kristin field and the Lavrans field are major discoveries, and contain 1200M barrels oil equivalent of gas and condensate (Storvoll, Bjørlykke et al. 2002).

Most of the deeply buried reservoirs at Haltenbanken and in the Northern North Sea offshore Norway are known to be significantly overpressured (Hermanrud and Marit Nordgrd Bols 2002). Although we find many of the same geological features in the Søgne basin, see e.g. (Petersen and Brekke 2001), already from its location one can notice several uncertainty factors:

- Overpressure in well

* Due to lack of obtainable data, information and results from the uncertainty analysis may or may not provide a realistic picture of the current situation of the Trym field.

- Weather condition
- Sea bottom condition
- Marine growth condition
- Traffic and exposure to dropped objects

The uncertainty arising from the poor predictability of overpressure and its impact on drilling costs and prospect evaluation is a global problem facing all explorers in areas prone to overpressure from causes varying between rapid sedimentation to tectonically active margins. It is extremely important to be able to diagnose overpressured units when drilling through them. This is because the drilling mud weight (density) must be adjusted to compensate. If not properly adjusted there is a risk that the pressure difference down-well will cause a dramatic decompression of the overpressured layer and result in a blowout at the well-head with possibly disastrous consequences. There are a number of operational challenges that exist alongside varying pressure regimes, including high bottom-hole temperatures, complex structural variances, and a canopy of salt that sits over much of the play, which makes the use of seismic data to visualize sub-salt structures largely ineffective (Dodds, Fletcher et al. 2001).

However, most of the risks involved with large overpressure are related to the initial phases of such a project, i.e. in the design phase and calculations regarding the drilling of wells. The wells in the Trym field are already finished, and hence the related risks by using calculations from Lavrans seem to have surpassed. With regard to inspections, the overpressure and related information about causes and consequences of this condition must be further addressed in order to properly assure safety.

The weather conditions in the two fields have some variations, although they are found to be largely similar. The temperatures for the Kristin platform have during the recent year varied from 17.2 degrees C as the hottest and -5.0 degrees C as the lowest point. Average wind varies from approximately 5 m/s to 8 m/s. The Eldfisk platform, close to the Trym field, measures a maximum temperature of 18.4 degrees C and a minimum temperature of -2.1 degrees C. Average wind varies from approximately 6.0 m/s to 10.0 m/s (Meteorologisk Institutt). Of course, these are estimates based on historical data and contain a small degree of uncertainty. This uncertainty is judged to be of a non-critical character as variations in the temperatures need drastic changes before they have any effect on the risk picture. This can be shown by assessing the sensitivity.

The condition of the sea bottom, both with regards to unevenness (free span, etc.) as well as growth and biological aspects, can cause major hazards when laying and securing the pipeline. Due to an uneven seabed, tidal currents or scouring, some pipelines may develop free spans. A free span on a pipeline is where the seabed sediments have been eroded or scoured away and the pipeline is no longer supported on the seabed. Important issues such as bending moments in the pipe and the need for trench excavations and wave-induced seafloor dynamics are necessary to study before laying the pipeline. During operation, sea bottom conditions may cause the need for higher frequency inspections at certain locations along the pipeline. The differences between the two field sites may be very different. This must be checked and assessed properly. Without proper documentation of sea bottom conditions, the uncertainty is judged to be quite significant.

Marine growth is a major reason to perform regular maintenance on subsea installations and pipelines. Marine growth adds mass and hydrodynamic loading to pipelines and riser systems.

This disadvantage may translate into increased stresses in the systems; decreases fatigue performance and additional tension requirements. Remote Operated Vehicles (ROV's) are often used to remove marine growth by deploying high pressure water jets or scrubbers. The thickness of the marine growth is calculated during inspections to assess the need for removal (mcs 2009). The use of an inspection interval from Lavrans applied on the Trym field causes rather large uncertainties, as the extent of the marine growth may be more or less similar. A worst case scenario can lead to higher maintenance costs due to an extensive marine growth removal job or even the need to repair pipelines where stress has caused cracks.

Depending of the traffic and exposure to dropped objects - hazards caused by fishing boats and fishing nets etc. - the need for extra protection, e.g. to bury the pipeline, might arise. Pipelines can be trenched into the seabed using a plough and then backfilled with the seabed spoil from the trench. This method is typical for smaller diameter pipelines, where as larger diameter pipelines are laid on the seabed. Smaller diameter pipelines are vulnerable to damage from heavy trawl doors, beam trawls or clump weights and there is a risk of serious environmental impacts if a pipeline is damaged and a leakage occurs. Also if free span occurs, the pipelines present a serious danger to fishing activity, especially trawl doors, clump weights or any towed gear, as they can become trapped under the pipeline and will be extremely difficult to recover, see figure below. In 1997 a Scottish fishing vessel was lost as a result of becoming stuck under a pipeline span (FishSAFE 2009).

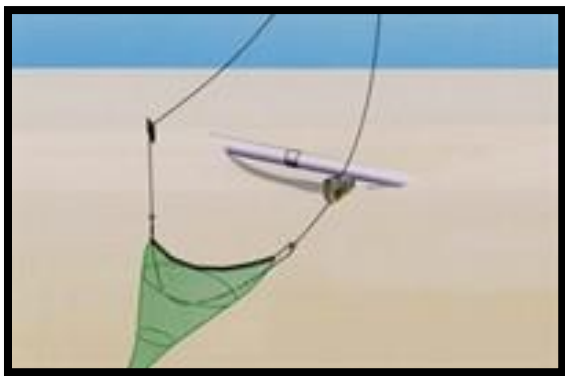


FIGURE 14 DOOR SNAGGED UNDER A PIPELINE (FISHSAFE, 2009)

For the reasons mentioned above, an assessment of the vessel traffic and exposure to dropped objects is necessary to perform separately for the two fields. Fishing activities may be significantly different from that performed around the Lavrans field to that which is performed around the Trym field. If not properly investigated, the uncertainty is seen as critical.

Concluding remarks on the “Lavrans-shortcut”

The uncertainty factors found in the assumption that the Trym field is identical or similar enough for reuse of data are of varying criticality.

1. Overpressure in well has been judged to have a Low degree of uncertainty as investigation of both sites have been made and show a large degree of resemblance. The degree of sensitivity is however Medium, due to the potential damages larger pressure differences can make. The degree of importance is Low/Medium because the wells have already been drilled, and so most of the threats are eliminated.

2. Weather conditions have a Low degree of uncertainty as data of weather history are easily obtained and show very similar conditions for the two fields. The sensitivity is also Low, as drastic changes in weather are needed to have an impact on the system performance. Degree of importance is also Low.
3. The sea bottom conditions have a High degree of uncertainty due to lack of documentation for the Trym field. The degree of sensitivity is judged to be High because a fairly probable sea bottom condition can potentially lead to cracks in the pipeline. Degree of importance is therefore also High.
4. Marine growth conditions cause a Medium degree of uncertainty because weather and sea conditions are very alike, and so it is to a certain degree reasonable to assume similar marine growth conditions. Degree of sensitivity is High, due to potentially high extra maintenance costs if the assumption does not hold. The degree of importance is Medium/High, mainly because of the additional costs if the maintenance routines are not performed on an efficient basis.
5. Traffic and exposure to dropped objects have a High degree of uncertainty because studies of the Trym location with regards to this have not been documented and it is not seen as reasonable to believe that the data is the same as for the Lavrans site. The degree of sensitivity is also High because a reasonable amount of traffic and dropped objects can in a worst case scenario cause disastrous consequences. Degree of importance is therefore also High.

This is summarised and presented in the following table:

TABLE 11 THE LAVRANS SHORTCUT

| Uncertainty factor | Degree of uncertainty | Degree of sensitivity | Degree of importance |
|--------------------------------|-----------------------|-----------------------|----------------------|
| 1. The Lavrans-shortcut | M | M | M |
| 1.1 Overpressure | L | M | L - M |
| 1.2 Weather | L | L | L |
| 1.3 Sea bottom | H | H | H |
| 1.4 Marine growth | M | H | M - H |
| 1.5 Traffic | H | H | H |

Uncertainty number 3 and 5 - sea bottom and traffic/exposure to dropped objects - are seen as highly critical and if proper documentation of state does not exist, this should be assessed as soon as possible in order to secure safety and ensure compliance with regulations in force.

7.1.2 DATA RELATED TO THE PIPE MATERIAL DEGRADATION RATES

The data used to obtain the expected degradation rates of the pipeline comes from limited databases of similar historical pipe lines. The amount and relevancy of the databases are not sufficient in order to rule out a relevant degree of uncertainty. This is caused by several factors:

1. Data selection is based on the correct descriptions
2. Variations in size and material combination
3. The pipeline is based on new technology
4. Possibilities of hydrogen induced stress cracking (HISC)

Uncertainty related to the data selection used to describe the degradation rates of the pipeline is based on instability in choosing generic, historical data. The uncertainties come from three main causes:

- descriptions of similar installations may contain errors
- choosing the correct data; it is important to be certain of which types of similarities one is looking for
- adjustments and simplifications made in order to be able to use available data

All generic data may contain errors to some degree and must therefore be used with great care. By using different types of databases and basing conclusions and decision basis on as many different types of data and information sources as possible, the possibility of reaching a reasonable result increases. It is impossible to find a data source which is identical to a new installation – there will always be some differences. Simplifications in order to find data which fits the description of Trym has been made and these contain a degree of aberrancy which creates uncertainties. The generic data used comes largely from a company database which is assumed to contain somewhat limited information. The degree of uncertainty in this case is therefore judged to be Medium due to limited amounts of data. However, the installation does not contain much new, “on the edge” technology, and therefore the data obtained is seen as reliable. The sensitivity is however High because the consequences of erroneous data can potentially cause a very unreliable system.

Variations in size and material combination are mainly related to the pipeline. Pipelines come in several different dimensions and with several different material combinations depending on surroundings and needed characteristics of the pipeline. In the case of Trym there is a need to be aware of HIC, pressures, temperatures etc. The particular size and material combination is based on calculations which includes these aspects. The uncertainty lies within the calculations and the assumptions of the values of pressures, temperatures, hydrogen sulphide and other relevant characteristics. Thorough calculations have been made and relevant data have been used to obtain the best possible pipelines, hence the uncertainty is Low. In a worst case scenario of wrongly dimensioned pipelines with unsatisfactory material combinations, the pipeline would crack and most of the work would have to be performed from scratch. The sensitivity is therefore High.

General corrosion would normally be expected to cause minor leaks. Other corrosion mechanisms involving such agents as carbon dioxide, hydrogen sulphide and hydrogen-induced stress can develop faster and less predictably. Although this has been noted in the design brief, it still causes an additional uncertainty with regards to the degradation rates. Generic data is simply not sufficient in order to assess this uncertainty. The degree of uncertainty is therefore High as well as the degree of sensitivity.

The summary is shown in the following table:

TABLE 12 UNCERTAINTY IN DATA

| Uncertainty factor | Degree of uncertainty | Degree of sensitivity | Degree of importance |
|--|-----------------------|-----------------------|----------------------|
| 2. Data | M | H | M - H |
| 2.1 Data selection | M | H | M - H |
| 2.2 Variations in characteristics | L | H | L - H |
| 2.3 HISC (sour gas) | H | H | H |

7.1.3 OTHER RELATED INSTALLATIONS ARE FUNCTIONING

During risk assessments the focus has been on the Trym field alone and not so much on the tie-back to the Harald platform and other nearby installations. During the risk assessment on Trym, these have been assumed functioning. Failure modes existent on the Harald platform and wells close to Trym contain uncertainties with regards to the effect it will have on Trym, i.e. if the failure mode can pose a threat to the Trym field and, if so, what the consequences will be. Although there has not been a risk assessment which combines all the installations, there have been assessments for each one individually with related interfaces. With this in mind, the uncertainty is judged to be Low. To fully assess the sensitivity one needs to perform and complete a risk assessment. By doing a crude analysis based on the risk analyses from nearby installations one can judge the sensitivity. The sensitivity is in this case Low.

TABLE 13 UNCERTAINTY RELATED TO ASSUMPTION OF OTHER INSTALLATIONS FUNCTIONING

| Uncertainty factor | Degree of uncertainty | Degree of sensitivity | Degree of importance |
|-------------------------------|-----------------------|-----------------------|----------------------|
| 3. Other installations | L | L | L |

7.1.4 INSPECTION RESULTS ARE REPRESENTATIVE FOR THE WHOLE PIPELINE LENGTH

During inspections only parts of the pipeline will be inspected, not the entire length. Data are gathered from several sites along the pipeline which are meant to represent the pipeline as a whole in order to simplify the inspection. This results in uncertainties concerning the reliability of the inspections. Some of the main uncertainty factors:

1. The data collected are representative for the entire pipeline
2. Uncertainties in the results collected from the use of ROV's

When samples from the pipeline are used to represent an entire length, an important assumption is made; the result from the sample is equal to the results which would be made if the entire length had been inspected. This assumption contains a Medium degree of uncertainty, as this assumption is not always correct. Depending on the number of samples made compared to the entire length, it may be more or less erroneous. As the Trym pipeline stretches for no more than 5 kilometres, big differences in environment are not expected to be found and hence the assumption is on more stable grounds. However, unexpected errors may occur at a sight which is not under thorough inspection and may therefore not be discovered until an actual failure occurs. Such failures may for example include pipeline ruptures which can cause environmental damages, production shutdown and large economic consequences. Hence the sensitivity is High.

ROV's are much used in the offshore oil and gas industry as an alternative to divers during inspections. Some of the main issues concerning the use of ROV's are the visibility, sea state conditions, currents and manoeuvrability. The visibility provided by the ROV can be of different qualities depending on the water, e.g. very dirty water can cause some problems, and the ROV technology. Most ROV's in use today provide very good footage and have the advantage of storing the inspection results for further inspections at another time. Sea state conditions like currents and big waves in combination with the umbilical drag may cause problems for the ROV's manoeuvrability. Inspections may be postponed due to weather conditions. Based on this, the uncertainty as well as the sensitivity is judged to be Low.

TABLE 14 UNCERTAINTY RELATED TO THE ASSUMPTION OF INSPECTIONS BEING REPRESENTABLE FOR THE ENTIRE PIPELINE

| Uncertainty factor | Degree of uncertainty | Degree of sensitivity | Degree of importance |
|---------------------------|-----------------------|-----------------------|----------------------|
| 4. Inspections | M | M | M |
| 4.1 Data collected | M | H | M - H |
| 4.2 ROV | L | L | L |

7.1.5 VARIATIONS IN THE QUALITY OF THE MATERIAL

Materials such as concrete and steel often have unique qualities which may cause an effect on the material's abilities with regards to stress. In the risk assessment it is assumed that the characteristic of a material is a constant as long as the material combinations are the same. This is however not necessarily the case. Aberrancies often occur, especially in materials such as concrete. Testing of the materials as well as adding an additional "safety buffer" to the calculations is normally a regulatory process which in most cases increases the material reliability.

Other issues which can cause reduced material quality can for instance be purposely induced simplifications where necessary machinery or contents to produce a certain material are missing. Historical events have shown cases where such issues have been ignored in order to keep a project from further delay.

However, where good routines both for production and verification exist, such variations in the quality of the material should not be a big issue to the safety of the installation. The degree of uncertainty is therefore set to be Low. The degree of sensitivity is also set to be Low because reduction in material quality rarely cause big effect on the functionality of the installation, it simply increases the need for maintenance.

TABLE 15 UNCERTAINTY RELATED TO VARIATIONS IN THE QUALITY OF THE MATERIAL

| Uncertainty factor | Degree of uncertainty | Degree of sensitivity | Degree of importance |
|----------------------------|-----------------------|-----------------------|----------------------|
| 5. Material Quality | L | L | L |

7.1.6 FLEXIBLE FLOWLINE RISERS

Flexible risers have statistically been shown to tolerate less strain than rigid risers, and may fail in new and unforeseen ways. Because the flexible flowline risers are fairly new, especially with regards to degradation over time, there is no complete inspection method for mapping the condition of flexible risers. Inspection of technical condition must therefore be based on a comprehensive assessment of information from several inspection methods - which assesses parts of the riser separately. As the tools for necessary inspection are lacking, we also lack good opportunities for early warning of flaws compared to other types of risers. H₂S permeation can also be an issue in flexible risers and can create unforeseen negative events if not discovered in time. The uncertainty related to degradation rates and general condition have an effect on the inspection interval, as the flexible flowline riser shall need some extra monitoring compared to rigid risers. The degree of uncertainty is Medium, and degree of sensitivity also Medium.

TABLE 16 UNCERTAINTY RELATED TO THE FLEXIBLE FLOWLINE RISERS

| Uncertainty factor | Degree of uncertainty | Degree of sensitivity | Degree of importance |
|-----------------------------------|-----------------------|-----------------------|----------------------|
| 6. Flexible Flowline Riser | M | M | M |

7.2 RESULTS

The main results from the uncertainty analysis are gathered in a table as shown below:

TABLE 17 MAIN RESULTS FROM THE UNCERTAINTY ANALYSIS

| Uncertainty factor | Degree of uncertainty | Degree of sensitivity | Degree of importance |
|------------------------------------|-----------------------|-----------------------|----------------------|
| 1. The Lavrans-shortcut | M | M | M |
| 2. Data | M | H | M – H |
| 3. Other installations | L | L | L |
| 4. Inspections | M | M | M |
| 5. Material quality | L | L | L |
| 6. Flexible Flowline Risers | M | M | M |

From this summary one can separate the uncertainty factors and focus on those which have a medium or high degree of importance, i.e. no. 3 and no. 5 does not need much further attention and can hence be skimmed through without spending time and resources deciding on how to assess the uncertainty.

As for the other uncertainty factors in the list it can be interesting looking at the root factors for the importance by assessing the results from the section above, i.e. the underlying uncertainty factors which were assessed in the main uncertainty analysis. In order to assist in the decision making process, visualisation of the uncertainties can prove helpful. We use the Lavrans-shortcut as an example, as the importance factor indicates the need for further attention.

7.2.1 VISUALISATION

Visualisation of the results of the uncertainty analysis can be shown in several ways. In this case study an example of the bubble matrix will be shown.

From the uncertainty analysis we have the root factors:

1. Overpressure (M - M)
2. Weather (L - M)
3. Sea bottom (H - H)
4. Marine growth (M - H)
5. Traffic (H - H)

The degree of importance - and hence also degree of uncertainty and sensitivity - is indicated in the brackets.

From the earlier analyses and calculations which have been performed, we deduce the bubble matrix:

TABLE 18 BUBBLE MATRIX BASED ON THE RESULTS FROM THE UNCERTAINTY ANALYSIS OF TRYM

| CoF PoF | 5 Insignificant | 4 Minor | 3 Local | 2 Major | 1 Massive |
|------------------------------------|---------------------------|-------------------|-------------------|-------------------|---------------------|
| 1 $>10^{-2}$ | | | | | |
| 2 10^{-3} to 10^{-2} | | | | 3 | |
| 3 10^{-4} to 10^{-3} | | | 4 | 5 | |
| 4 10^{-4} to 10^{-5} | | 1 | | | |
| 5 $<10^{-5}$ | 2 | | | | |

The matrix shows an easily interpretable method for discovering the root uncertainty factors which needs further assessments. In this case it is clear to see that number 3 (sea bottom) is the most critical, while numbers 4 (marine growth) and 5 (traffic) come in a good second and should also be further assessed.

As we have no calculations of exact PoF, we use the numbers from 1 through 5 to indicate the probabilities of the events. This is a purely qualitative method which is based on the background information given in the above section where the uncertainties are described. In most cases where probabilities have been calculated, one will combine the two information sources when found fruitful.

Recommendations for lowering the degree of uncertainty may be presented to the management for managerial judgement.

7.2.2 REPRESENTATION

The representation of the Lavrans-shortcut uncertainty factor should contain a short and precise description of the issues at hand as well as degree of uncertainty, sensitivity and importance. A scheme similar to the one presented in figure 10 is recommended. Where tables, matrices etc. have been made for better visualisation and easy understanding, this should naturally be included. Uncertainties which are found not acceptable shall be clearly marked with a recommendation of improvement. Any other recommendations for improvement can be added at the end of the document.

7.2.3 UPDATING

Updating of the uncertainty analysis shall be performed after managerial judgement and decisions. The impact of the changes made to the installation shall be assessed in order to secure new uncertainties from arising from the changes, as well as ensuring that the improvements work as intended by lowering the uncertainties to an acceptable level.

7.3 VERIFICATION

When performing risk based verification all documents of design, calculations etc. shall be verified. This information should be readily available from the ERBI assessment. We continue to use the Lavrans-shortcut as an example when continuing with the RBV process.

Firstly, one needs to define the level of verification and objectives. The level of verification will depend strongly on the level of importance found in the uncertainty analysis. As the level of importance reflects the reliability of the factor, it also creates a reflection of the verification grounds. I.e. the higher the degree of importance, the more likely it is that the factor may not comply or be restricted/recommended to perform alterations and improvements.

Again, a table can be used:

TABLE 19 UNCERTAINTY FACTORS, LEVEL OF VERIFICATION AND OBJECTIVES

| Uncertainty factor | Level of verification | Objectives |
|--------------------------------|-----------------------|---|
| 1. The Lavrans-shortcut | M | Ensure compliance with rules and regulations with regards to the assumption that the Trym field is similar/ identical to the Lavrans field. |
| 1.1 Overpressure | L - M | Verify assumption |
| 1.2 Weather | L | Verify assumption |
| 1.3 Sea bottom | H | Verify assumption |
| 1.4 Marine growth | M - H | Verify assumption |
| 1.5 Traffic | H | Verify assumption |

In this case the level of verification is identical to the degree of importance. In most cases this will be true, but use caution when assuming this. The objectives are shortly summarised in the table also. In most cases the objectives will be reported in an agreement between the third party which is to perform the verification and the owner/operator of the installation. This document will show a more thorough plan and objectives, and may also include costs and payments to the third party verifiers.

The verification plan will in this particular case mostly consist of ensuring the assumptions by reviewing sources and ensuring compliance with Danish and Norwegian legislations. When executed, a non-conformance report will show which, if any, factors will be imposed changes of improvement.

The Norwegian Framework regulations state in chapter VII "Design and outfitting of facilities and conducting activities in the offshore petroleum activities", several sections with regulations which are not adequately met (The Petroleum Safety Authority Norway 2010):

- **Section 46: Oceanography, meteorology and earthquake data**

The petroleum activities shall be based on representative oceanography, meteorology and earthquake data. If such data are not available, collection of such data shall be initiated so that the necessary data are available for planning and implementation of the petroleum activities...

- **Section 48: Duty to monitor and record data from the external environment**

To ensure that the decision basis and knowledge about the marine environment is sufficient to maintain an acceptable environment condition, the operator shall monitor and record data from the external environment. Sufficient information shall be obtained to ensure that all pollution caused by own activities is detected, mapped, assessed and notified, so that necessary measures can be implemented.

The above shows non-conformance in at least two of the uncertainties; number 2 and 4, weather and marine growth, and must be added to the non-conformance report.

8. DISCUSSION OF RESULTS

The Extended Risk Based Inspection routine gives an improved view of the risk picture which creates better grounds for decision. The results have certainly provided a somewhat different view on many of the risk factors assessed in the previous sections, which normally may not have been discussed. However, the final results consisting of an inspection routine might not be different from the result if a normal RBI was executed instead.

The assumption of similarity between the two installations Lavrans and Trym have shown to be fairly reasonable, but contain a few larger uncertainties and regulatory non-conformances which have to be assessed. However, none of which necessarily will change the inspection routines significantly.

Uncertainties in the data used in the assessment of risk have been shown to be of a more serious state than first assumed. Generic data which come from a company database provide a limited number of sources which may or may not be relevant “enough” to be considered as reliable data. When reviewing the generic data, a number of underlying uncertainty factors may arise and create a need to change the inspection routines if and where the generic data cannot be relied upon. The inspections of, say, the pipelines with regards to subsea growth may be less frequent because information about nearby installations provide a significantly more reliable data source than first assumed. While on the other hand, inspections of the state of the sea bottom will need a more frequent inspection plan as the geological data of the sea bottom state is seen as very unreliable.

Uncertainty regarding the inspections will not have an impact on the primary issue of the inspection routines, but may provide as good grounds for decision of whether the inspection routines are of an ideal and economical frequency. Where the inspections give weak results it may be necessary to increase the inspection frequency in order to obtain more data and hence receive a more reliable result.

The flexible flowline risers show uncertainties with regards to the H₂S issue, which may have an impact on the inspection plan. If the inspection routine has to take consideration of the uncertainties which are to be found in H₂S permeation as well as lack of consistent data of strain limitations in the flexible risers, when making a decision of the inspection frequency.

8.1 THE FINAL INSPECTION PLAN

In the normal RBI assessment, estimates and probability play a big role and the results reflected in the inspection plan may be significantly influenced by such probabilistic values. The relative frequency-based perspective gives an impression of true values which does not exist in the attempt of trying to predict degradation rates and future failures. The final outcome of the inspection plan may not necessarily be much different in the ERBI method compared to normal RBI, but an improved understanding of the situation at hand does assist in avoiding potential pitfalls. An example of this can be shown in the case of uncertainty regarding H₂S permeation in the flexible flowline risers – the degree of uncertainty indicates a higher need for awareness of the phenomenon and the degree of sensitivity motivates a cautious policy. If solely based on generic values of probability, the risk picture might be completely different, simply because the databases do not contain much data on this area and hence are not sufficient to be relied upon in such a degree.

The decision makers will with the ERBI method have access to the assumptions made during the risk assessments, and may justify the need for a more cautious handling of certain risk factors, based on the information given by the degree of uncertainty, sensitivity and importance. This secures a second opinion given by others than the assessors of the risk analysis, and hence provides an additional quality assurance.

9. CONCLUSION

The RBI method has over the recent years proved to show fruitful results with regards to proactive risk measures in the offshore oil and gas industry. The methodology continues to show results of increased safety, more reliable and predictable systems and a more economical routine for maintenance and inspection activities. However, there has been shown weaknesses in the method; unreliable calculations, data and judgements which have the potential of causing system failures and have destructive consequences. This shortcoming has been traced back to a lack of focus on the uncertainties in the risk analysis.

In order to assess this weakness, the ERBI method was developed. The basic idea behind the method is that uncertainties are communicated to the management through an extended uncertainty evaluation which integrates the results from the risk analysis and the uncertainty analysis. However, how this is performed in practice is not yet clear.

This thesis presents and discusses the ERBI methodology and provides an enhanced description of how to perform the ERBI method. The methodology is taken a step further; from a theoretical framework to a recommendation of practice. The recommended practice enhances some of the basic ideas of the ERBI methodology and maximises the benefits by using the method.

The additional assessments of uncertainty and sensitivity produce some increase in the time needed to perform the process, as well as resources required. The purpose of the thesis was to show that with an effective method of performing the ERBI, the increase of resources could be minimal.

The extra time and costs due to uncertainty factor assessments should initially not be very large compared to the overall costs of the RBI. The thesis proposes a closer cooperation between the different risk analyses which exists in a project; when recognizing the similarities in the risk assessments as well as the advantages of including uncertainty assessments in more risk assessments than just the RBI, a clear possibility for saving resources is evident. By reusing information and opening up for an enhanced information flow, the resources introduced by incorporating uncertainty may be caught up with when looking at the greater risk picture, i.e. from the initial phases of a project and forth. This includes amongst other things LCC assessments from the design phase, QRA's, FMEA etc. which have been performed in the earlier stages of the project. After a finalised ERBI assessment, the information gathered here can further be reused in an RBV assessment. This does not only provide quality insurance, but also allows the uncertainty factor assessment to be followed through during all future phases and risk assessments.

Further measures for effectively performing the ERBI have been introduced. These include, amongst other things, diagrams, tables and matrixes designed for enhanced understanding of a situation as well as saving time by sticking to a preset scheme. These measures allow for personal interpretation to a certain degree, but at the same time reassure the quality in the assessments by providing a set of guidelines. Common pitfalls and potential confusion regarding the meaning of the results are to a greater extent avoided when following the recommendation. Its performance is simple, but yet thorough so that no vital information gets lost in the process.

A case study is performed in order to describe and give an idea of how the method works in practice, and what results can be found. The findings show elements of uncertainty which may

not have been assessed when applying the RBI method as performed today, and have the potential of changing the inspection plan as well as the entire risk picture. The overall results of the case study do however only give the reader an idea of how the recommendation with regards to information flow between different risk analyses is executed. To get the full insight of this particular progress, a real case with real risk assessments and proper documentation is needed.

It is believed that the RBI method works sufficiently, however one of the main weaknesses is that a risk perspective is not properly defined in these frameworks. This further influences how risk is to be understood and hence great care has to be shown. The ERBI has a clearly defined risk perspective and the recommended practice built around this perspective creates quality insurance with regards to hidden uncertainty factors. Too much focus on uncertainty factors would however not serve the purpose of creating attractiveness to the ERBI – the workload and demand of resources would simply be too great, at the same time as an overload of uncertainty factors may contribute in a confusing way if not presented correctly. The guidelines provided in this thesis are believed to enclose measures which assess functions to clarifying the uncertainty assessment and corresponding representation of results, as well as enhancing its effectiveness.

In regards to the resources spent in order to perform ERBI instead of RBI, it is evident that some additional resources, both time wise and with regards to the overall costs, must be accounted for. It is however believed that the benefits by applying ERBI outweigh the additional amount of resources needed.

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